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Experimental Studies on Progressive Collapse Behavior of RC Frame Structures: Advances and Future Needs

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Abstract

In the recent two decades, the progressive collapse of reinforced concrete (RC) frame structures attracted unprecedented research interests in the structural engineering community. Experiments are regarded as an essential method in this field since actual cases can barely provide sufficient and effective data to support rigorous research. In this paper, prevailing experimental assumptions and configurations among over 100 series of experiments are quantitatively revealed by a bibliometric collection based on systematic search in an academic database. Since numerous experiments have been reported on the progressive collapse of RC frame structures, this paper subsequently presents a state-of-the-art review summarizing both experimental consensuses and controversies constituted by three main aspects: (a) static mechanisms, (b) dynamic behavior, and (c) threat-dependent research. The significance of secondary mechanisms, existing problems of dynamic effects, and potential flaws of the threat-independent assumption are discussed in detail with experimental findings. Future needs are emphasized on research targets, correlations between experiments and design, dynamic effects, threat-dependent issues, and retrofitting. These recommendations might help researchers or designers realize a more reliable and realistic progressive collapse design of RC frame structures in the future.

Keywords: progressive collapse, RC frame structures, experimental study, anti-collapse design, dynamic effects, threat dependent

1 Introduction

If structural members failed under extreme loads like natural disasters, explosions, vehicle impacts, fires, etc., the local damage might be disproportionate to the final collapse scale, by which the term progressive collapse or disproportionate collapse is defined. Progressive collapse accidents attracted widespread attention include Ronan Point Apartment, New World Hotel, A. P. Murrah Federal Building and the 9/11 Attacks. The structural engineering community began to extensively and profoundly research the progressive collapse and structural robustness problems of building structures, especially since the 9/11 Attacks. Considering the progressive collapse is featured with low-probability-high-consequence (LPHC) that results in data scarcity of actual accidents, the understanding of progressive collapse-resisting mechanism heavily relies on the experimental study. RC structures earned considerable concerns in the field of progressive collapse research, and more than one-half of the papers are relevant to RC structures, especially the cast-in situ RC frame structure.

Some of the most representative studies from different aspects like analytical theories, experimental studies, and numerical analyses have a profound influence on subsequent studies, for example, the simplified assessment framework proposed by Izzuddin et. al. (2008), and Vlassis et. al. (2008), the quasi-static experiment conducted

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by Yi et. al. (2008), and the macro-model numerical analysis developed by Bao et. al. (2008), and Khandelwal et. al. (2008). Also, experimental studies concerning slab effects are conducted by Qian and Li (2012c,2013d), Qian et. al. (2015), and Ren et. al. (2016). Further, several deficiencies in existing progressive collapse codes and design guidelines were discussed by Qian and Li (2015). Adam et. al. (2018) comprehensively reviewed advances of progressive collapse and building robustness since the twenty-first century. Factors influencing progressive collapse resistance of RC frame structures were presented by Azim et. al. (2019). Despite some critical issues about the progressive collapse of RC structures have been discussed by Qian and Li (2015), Adam et. al. (2018), Azim et. al. (2019), Alshaikh et. al. (2020), and Kiakojouri et. al. (2020), this review differs from these works by three aspects: (1) a statistics on existing experimental studies is first presented at this scale to facilitate both experienced and newly attracted researchers to tag classic and track latest works; (2) the progressive collapse behavior is discussed based on experimental findings, which could be helpful for quantification and further codification of load-resisting mechanisms, both primary and secondary, neither of which has been systematically digested by existing codes and design guidelines; and (3) the threat-dependent assumption which attracted relative minor attention is emphasized.

One origin of complexities embedded in the progressive collapse behavior is dynamic effects. A general conclusion was drawn based on linear single-degree-freedom system that a step loading with sufficient duration will produce a dynamic magnification factor of 2 (Clough & Penzien, 1993). However, the structural performance of actual buildings is directly influenced by geometrical and material nonlinearity, which cannot be reflected in an idealized SDOF system. It is worth noting that the factor is called "dynamic magnification factor" or "dynamic increase factor" in different references, and some researchers proposed their own definitions. Considering the term "dynamic increase factor" has been used in the strain rate effect, the term "dynamic magnification factor" is generally accepted in this paper to keep consistency with the dynamics discipline (Clough & Penzien, 1993) and to avoid ambiguity unless studies state other definitions in its context. Codes and design guidelines have already taken dynamic effects into considerations (DoD, 2009; GSA, 2013), but the accuracy of proposed algorithms to calculate the dynamic increase factor (DIF) and load increase factor (LIF) was not experimentally verified. Some researchers convince that these algorithms are still disputable (Liu, 2013; Qian & Li, 2012a).

Another origin of complexities is the diversity of triggering events. Engineering practice demonstrated that progressive collapse of building structures could be triggered by over-loading, quality deficiencies, explosions, fires, impacts, etc. Nonetheless, the threat-independent assumption is still widely adopted in current studies, so experimental reports of interactions between extreme events and structural behavior of building structures are relatively few.

Experimental studies on RC frame structures and some of RC flat-plate structures in the last 20 years were collected in this paper. The concerns include static and dynamic experiments, threat-independent and threat-dependent experiments, and experiments in any specimen formations. Focusing primarily on RC frame structures, this review is organized as follows: (1) bibliometric data about present experiments; (2) discussion on static mechanisms; (3) discussion on dynamic behavior; and (4) status quo and necessity of threat-dependent experiments. Finally, the authors summarized the main viewpoints and suggestions of this paper for future research.

2 Bibliometric Statistics

Referring to the classification method in Adam et. al. (2018), experiments were divided into beam–column connections, sub-assemblages (with or without slabs), planar frames, spatial frames, actual buildings, and flat-plate sub-assemblages. Sub-assemblages refer to specimens that only simulate local members within the range directly affected by column removal. A typical instance is axially restrained two-span beams, which are employed to investigate compressive arch action (CAA) and catenary action (CA) in many experiments. Planar frames are beam–column systems with two or more floors so that Vierendeel action can be simulated. Spatial frames are three-dimensional beam–column–slab systems with two or more floors, and experiments employing spatial frames usually investigate the membrane action of slabs. Actual buildings are usually buildings scheduled for demolition. RC flat-plate structures are individually listed because its load-resisting mechanism, which is dominated by continuous shear damage of column–slab joints, is distinctly different from frame structures.

Scopus database is employed to establish this data pool by following search combinations:

1. (TITLE (progressive AND collapse) AND TITLE (experimental OR test) AND NOT TITLE (steel))
2. (KEY ("progressive collapse") AND KEY ("reinforced concrete") AND KEY (experiment OR test))
3. (TITLE (disproportionate AND collapse) AND ABS (experiment OR test) AND NOT KEY (steel))

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Also, complete bibliometric details are provided in Additional file 1: Appendix S1.

Figure 1 illustrates that experimental studies on RC frame structures are increasing annually. Sub-assemblages are the most prevailing formation in these studies (Fig. 2). Figure 2 also shows the number of experimental studies classified by triggering events, which is known as threat dependent or threat independent, is still uneven at present. With 85% of studies adopted the threat-independent assumption, explosion-related and fire-related studies are still rare, and no impact-related progressive collapse experiment is reported. Threat-dependent problems have not been investigated sufficiently comparing to their threat-independent counterparts.

3 Static Mechanism Studies

Static experiments are the predominant method to investigate progressive collapse-resisting mechanisms of building structures, and the alternate path method (APM), which is consistent with the equivalent static method in seismic design, is adopted in common codes and design guidelines like UFC 4-023-03 and GSA guideline (DoD, 2009; GSA, 2013). Some typical scenarios like

the external, corner, internal, and penultimate exterior column removal have been studied. According to these studies, the influence of single column removal is limited to the vicinity of the removed column (Jian et al., 2016; Sucuogˇlu, 1994), i.e., beams and columns within the same bay. Because of this finding, the fidelity of sub-assemblage experiments can be endorsed.

3.1 Progressive Collapse-Resisting Mechanism

Experimental studies of RC frame structures under progressive collapse in the recent decade confirmed that the progressive collapse resistance can be provided by resisting mechanisms like beam action, CAA, CA, and Vierendeel action. Beam action and Vierendeel action mainly provide resistance when structures behave at a small deformation stage when plastic hinges are still effective. CAA only exists in locations where peripheral members can provide sufficient lateral restraints to exert thrust. In most cases, the loss of corner, side, penultimate side, and antepenult side columns leads to defective activation or absence of CAA, so these scenarios face a higher progressive collapse risk. CA becomes dominant after plastic hinges of beam–column joints fail and the state of longitudinal reinforcement in beams becomes tensile. Experimental observations suggested that CA can be activated when the middle column stub's vertical displacement exceeds adjacent beams' depth. Resisting mechanisms are briefly introduced because they have been organized and discussed by some definitive studies in advance, and more detailed discussion can be found in (Azim et al., 2019).

An early experimental study conducted by Yi et. al. (2008) on an RC planar frame and subsequent studies conducted by Sasani and Kropelnicki (2008), Su et. al. (2009), Qian and Li (2012b), Stinger and Orton (2013), Yu and Tan (2013a), and Yu and Tan (2013b) on
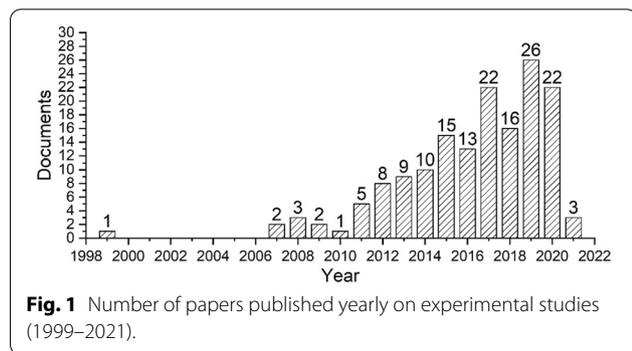

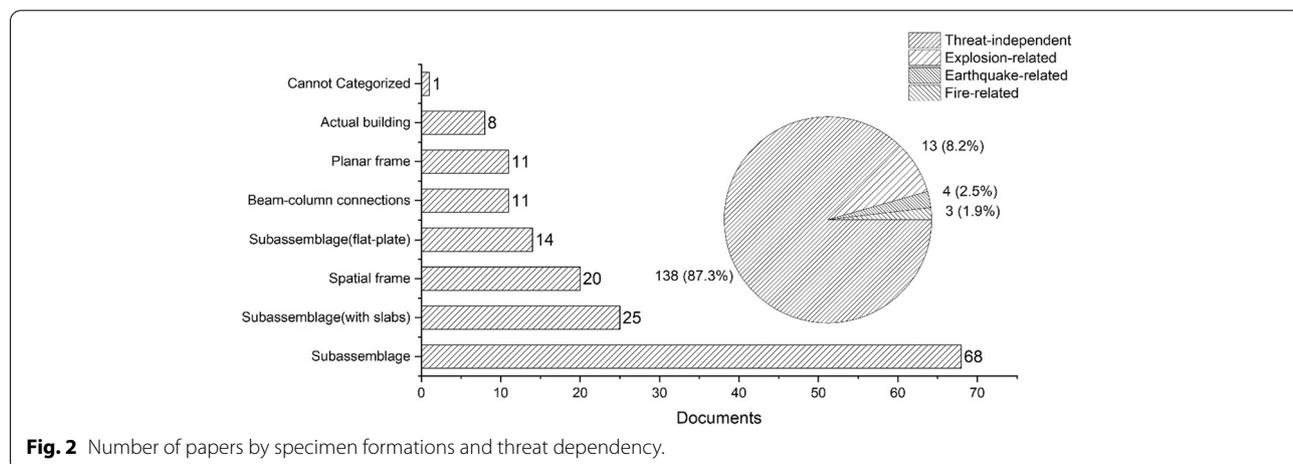**Fig. 1** Number of papers published yearly on experimental studies (1999–2021).

Fig. 2 Number of papers by specimen formations and threat dependency.

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sub-assemblages and planar frames indicated that progressive collapse resistance of RC frame structures is significantly enhanced by CAA and CA. Factors like the reinforcement ratio, the reinforcement layout, the anchorage of longitudinal reinforcement, and the boundary condition also influence the progressive collapse resistance. The failure of CA, which is commonly deemed as the last defense of progressive collapse, could be caused by longitudinal rebar fractures of adjacent or middle beam–column joints in most cases, as well as pull-out of discontinuous reinforcement sometimes.

Currently, consensuses have been achieved on primary load-resisting mechanisms of RC frame structures in progressive collapse. Adam et. al. (2018) concluded that primary load-resisting mechanisms are constituted by beam action, CAA, CA, membrane action, and Vierendeel action. Differing from other actions at the component level, Vierendeel action is defined as a resisting mechanism of structural level in which upper loads are redistributed to peripheral structural members in the form of shear forces of beams above the removed column. Vierendeel action is differentiated from the beam action sometimes because they depict different aspects of progressive collapse behavior of frame structures, the former explains the alternate path of loads, and the latter is a force state of structural members. The contribution of non-structural members should also be accounted. Azim et. al. (2019) argued that the span–depth ratio and the longitudinal reinforcement ratio are the main factors that influence progressive collapse resistance. Alshaikh et. al. (2020) summarized the influence of span–depth ratio and reinforcement configurations on CAA and CA.

Some experimental data are utilized to train gene expression models predicting structural capacity under CAA and CA, like Azim et. al. (2020), and Azim et. al. (2021). However, a worrisome fact is that codes and design guidelines can hardly provide practical experiment-validated suggestions to non-linear analysis, which results in an inconsistency between progressive collapse design and experimental research. An obvious example is that only the resistance contributed by primary members is accounted for in DoD and GSA guidelines, while experimental studies indicated that this simplification substantially underestimates the resistance of actual buildings (Qian & Li, 2012c, 2013d). The existence of secondary members like slabs and infill walls not only provided considerable resistance against progressive collapse but also altered the failure mode of beams and columns.

3.1.1 Slab Membrane Action
Slabs provide extra resistance by compressive or tensile membrane action under different stress states. Gouverneur et. al. (2013) investigated the load–deformation response of one-way slabs in which the tensile membrane action is observed. Quantified conclusions of slab membrane action studies are collected and presented in Table 1 (Chu et al., 2016; Du et al., 2019, 2020; Lim et al., 2017b; Lu et al., 2017; Qian & Li, 2012c, 2013d; Qian et al., 2015; Ren et al., 2014, 2016). The effects of RC slabs could be studied from two aspects. On the one hand, slabs act as compressive/tensile membranes. On the other hand, the existence of slabs alters the structural capacity of beams because its flexural and torsional stiffness will be increased, which is known as the flange effect, in which the effective flange width is determined by beam span and by the relative thickness of the slab in ACI 318-14. Relevant studies generally suggested that slabs are beneficial in terms of improving the ultimate load-bearing capacity of structures. However, the degree of influence obtained in different tests varies greatly because parameters like beam depth, beam span, location of column removal, slab thickness, and seismic design could be of influence simultaneously. Besides, it was also found that slabs affect the characteristics of RC frame structures like load-resisting mechanisms (Du et al., 2019; Qian & Li, 2013d; Qian et al., 2015), failure mode (Qian & Li, 2012c; Ren et al., 2016), and load redistribution (Qian et al., 2015).

For slabs by which vertical displacements are restrained, methods based on plasticity theory have been proposed for analyzing compressive and tensile membrane (Bailey, 2001; Park & Gamble, 1999). The tensile membrane action of slabs has also been estimated based on experimental results (Qian et al., 2015). An analysis showed that the tensile membrane action provides an additional 36% collapse resistance when the vertical displacement reaches its maximum (Jian et al., 2016).

However, the compressive and tensile membrane action might not be quantified because when actual structures

Table 1 Summary of quantified influence by slabs in experimental studies.

Index	Degree of influence	Source
Yield strength and initial stiffness	48.9% and 27.6%	Qian and Li (2013d)
Ultimate capacity	40.7–63%	Qian and Li (2012c)
Beam action capacity	246.20%	Qian et. al. (2015)
Collapse resistance	98–146%	Lu et. al. (2017)
Ultimate capacity	45.40%	Ren et. al. (2014)
Ultimate capacity	38–145%	Ren et. al. (2016)
Ultimate capacity	40–55%	Lim et al., (2017b)
Ultimate capacity	75–145%	Du et al., (2019)
Ultimate capacity	35.7–334.6%	Chu et al., (2016)
Ultimate capacity	22–278%	Du et al., (2020)

are close to collapse, the slabs in the damaged area are at different stages of stress, and the reinforcement configuration of slab portions deforming together with beams may also be different. A conservative consideration is accounting influence of slabs with limited width into beams, which is equivalent to a flat-plate structure considering only slab strips on columns.

It is still necessary to further develop analytical models for the membrane action of slabs. After all, a more efficient progressive collapse design can be achieved if the capacity contributed by slabs is fully utilized. Also, test results (Qian & Li, 2012c; Ren et al., 2016) indicated that slabs might change the load distribution pattern of original beam–column structures. The slabs affect the deformation compatibility of structures resulting in over-reinforcement damage of beams and replace the CA of beams with the tensile membrane action of slabs as the last defense against progressive collapse.

3.1.2 Infill Wall Effects

Some actual accidents show that infill walls play an important role in resisting the progressive collapse of RC frame structures (Al-Khaiat et al., 1999; Sucuogˇlu et al., 1994). Researchers such as Stinger and Orton (2013), Shan et. al. (2016), Li et. al. (2016), Qian and Li (2017b), Brodsky and Yankelevsky (2017), Baghi et. al. (2018), Shan et. al. (2019), and Qian et. al. (2020a) have conducted experimental studies to address the infill wall effect. It is suggested that partial-height infill walls have only minor effects on the bearing capacity of RC frame structures while full-height infill walls, which act as equivalent compressive struts, increased the bearing

capacity of structures (Shan et al., 2016). Comparing with skeletal frames, infill walls with openings and infill walls without opening increased the maximum resistance force by 1.57 times (Shan et al., 2016) and 4 times (Li et al., 2016) (Fig. 3). Configuration of infill walls (with/without openings), ties to frames, and blocks and mortar strength all influence the infill wall effect. Besides, multiple studies argued that infill walls will reduce structural ductility while increasing the initial stiffness of structures (Baghi et al., 2018; Li et al., 2016; Qian & Li, 2017b; Shan et al., 2016). It is also worth noting that experiments conducted by Qian et. al. (2020a) suggested that deformation capacity of frames will not be reduced by infill walls. Also, Onat et. al. (2018) suggested that frames' ductility can be recovered if the infill wall is reinforced by horizontal bed joints.

In terms of theoretical analyses, Qian and Li (2017b) obtained the resistance force of compressive struts by crushing assumption and splitting assumption, respectively (Saneinejad & Hobbs, 1995), and the calculation suggested that the result from the splitting assumption is relatively closer to the experimental results. Baghi et. al. (2018) developed a macro-finite model using eccentric truss elements. In general, ignoring the effects of infill walls might lead to substantial errors in predictions of structural stiffness, strength, and failure modes. Meanwhile, a numerical analysis performed by Nyunn et. al. (2020) suggested that infill walls have no significant effect on the value of dynamic amplification factor (DAF), in which the detailed discussion is presented in Sect. 4.

The fundamental reason why infill wall effects affect the progressive collapse behavior of RC frame structures is
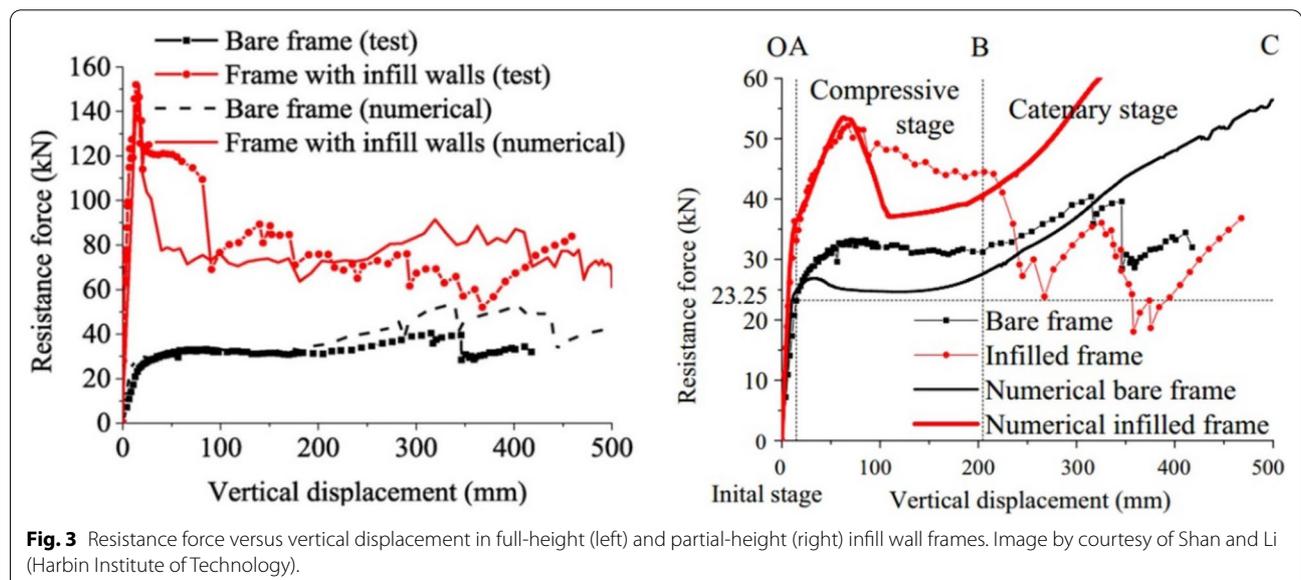

Fig. 3 Resistance force versus vertical displacement in full-height (left) and partial-height (right) infill wall frames. Image by courtesy of Shan and Li (Harbin Institute of Technology).

the formation of equivalent diagonal compressive struts. The above studies show that the load-bearing capacity increase by full-height infill walls is more pronounced than that of infill walls with openings (Li et al., 2016; Shan et al., 2016), which could be attributed to stress concentration in the corner area of openings. While there is room for further investigation on infill wall effects such as the spatial structures with slabs and relevant studies under dynamic loading, the key point is that infill walls change the failure mode of RC frame structures in progressive collapse because the failure of infill walls could also indicate the commence of progressive collapse. When evaluating progressive collapse performance of RC frame structures, the beneficial and detrimental influence of infill walls in actual conditions, which the research is still sparse, should be considered adequately.

3.2 Progressive Collapse Scenarios

3.2.1 Column Removal Locations

The most typical scenario in progressive collapse experiments of RC frame structures is the internal column removal of sub-assemblages. Significant CAA and CA can be observed if the sub-assemblages were efficiently restrained in the axial direction (Su et al., 2009). However, in actual accidents, external and corner columns are more susceptible to extreme loads (Glover, 1997). Structures would face a higher risk of progressive collapse if column removal occurred at locations where load-resisting mechanisms were confined.

Li and Yap (2011), and Qian and Li (2012b) conducted beam–column joints tests to investigate the discrepancies between internal and external removal scenarios. Results indicated different failure modes between the two removal locations. Lim et. al. (2017b) investigated the corner and external column removal scenarios, and experiments indicated that RC slabs are susceptible to flexural failure under corner column removal while punching shear failure under external column removal. Dat and Tan (2013), and Dat and Tan (2014) studied the collapse resistance of sub-assemblages under penultimate external and penultimate internal column removal scenarios, respectively, and the results indicated discrepancies of CA exist in different scenarios. Diao et. al. (2019), and Qian et. al. (2020d) studied progressive collapse resistance under penultimate and antepenult edge column removal scenarios, respectively. The results illustrated that column removal locations significantly influence the progressive collapse-resisting mechanisms of RC frame structures. Both Jian et. al. (2016), and Yu et. al. (2020a) studied structural behavior of sub-assemblages with slabs under side-middle (perimeter) column removal scenarios. Yu et. al. (2020b) further compared the side-middle and the penultiamte exterior scenarios.
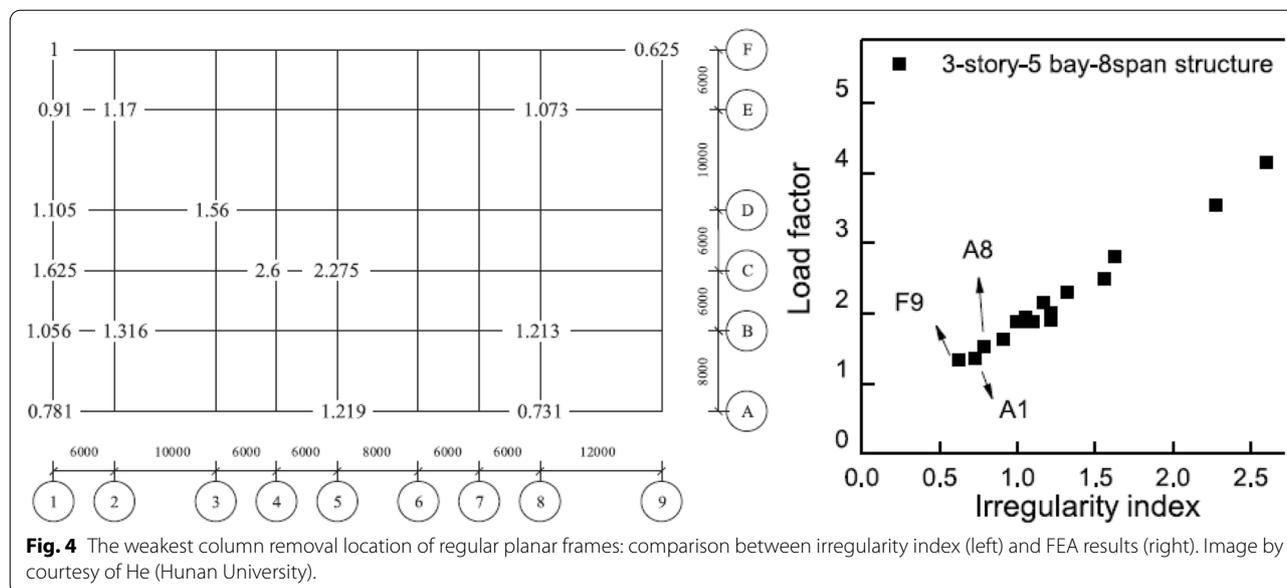
The results suggested that CAA and CA still exist in this scenario if strong lateral conditions are provided. Besides, a series of studies related to RC structures under corner column removal have been conducted by Qian and Li, including the membrane action (Qian & Li, 2012c), the static performance (Qian & Li, 2013c), the dynamic performance (Qian & Li, 2012a), and the drop panel effect of flat-plate structures (Qian & Li, 2013b), and the researchers proposed an analytical model to estimate the load–displacement relationship of RC structures under corner column removal (Qian & Li, 2013a).

Due to cost and time constraints, it is hardly possible to analyze all column removal locations through experimental methods. Some researchers pointed out that conflicting findings exist on the weakest column removal scenarios and proposed an irregularity index in which beam actions and membrane actions were considered to describe the weakest scenarios and applied it on irregular frame structures (He et al., 2019). As shown in Fig. 4, the irregular index predicts quite consistent conclusions with non-linear finite element analysis on the weakest column removal location. According to He et. al. (2019), the ratio of the collapse resistance under tensile membrane action to flexural strength of structures is sufficient to determine the weakest column removal location. Nevertheless, the study on the weakest column removal location needs further verification because of its over-simplified assumptions.

3.2.2 Multi-column Removal

Actual accidents (Gurbuz et al., 2019) and numerical studies (Kang & Kim, 2015) indicated that multi-column removal is possible to occur in impact accidents. The progressive collapse risk under multi-column removal scenarios is higher than the single column removal. Nonetheless, some demolition experiments suggested that resistance of actual buildings subjected to multi-column removal could be higher than anticipated because of the collaboration of several load-resisting mechanisms.

Sasani and Sagiroglu (2008), and Sasani et. al. (2011) conducted in situ explosion experiments on a 6-story and an 11-story building, respectively. No evident progressive collapse occurred in both experiments, in which the researchers ascribe it to bi-direction Vierendeel action. Qian et al., (2016, 2018c) investigated the influence of multi-column removal on RC frame structures and flat-plate structures. Results indicated that load-resisting mechanisms cannot be effectively motivated under multi-column removal. However, the punching shear failure and the consequent progressive collapse of flat-plate structures are prevented due to the compressive membrane action and the drop panel effect. Ma et. al. (2020) compared the progressive collapse behavior of RC

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Fig. 4 The weakest column removal location of regular planar frames: comparison between irregularity index (left) and FEA results (right). Image by courtesy of He (Hunan University).

flat-plate structures under several column removal scenarios. The results show that the simultaneous removal of two columns leads to a reduction in the ultimate load-bearing capacity of structures and increases the risk of progressive collapse. However, the ductility is higher under the multi-column removal. Xiao et. al. (2015) conducted experiments on a half-scale spatial frame. The frame kept elastic after losing a corner column and a penultimate corner column, but the partial collapse was observed after two external columns along the long-span direction were removed.

The above experiments show that the location of multi-column removal has a remarkable influence on the progressive collapse resistance of structures. RC frame structures will basically lose all resisting mechanisms under the scenario of adjacent corner column removal excepting the Vierendeel action. Considering design parameters (floor height, column grid layout, reinforcement detail, etc.) of actual buildings vary in a pretty wide range, it is not very practical that determining structures' progressive collapse performance solely rely on experiments. A reasonable analytical model supplemented by experimental validation of typical working conditions should be developed using known load-resisting mechanisms and experimental results so that the collapse risk of RC frames under two- or multi-column removal scenarios can be adequately determined.

3.3 Influence of Design Parameters
Design parameters like beam span, cross-section height, and reinforcement detail will definitely influence the progressive collapse performance of RC frame structures.

There have been experimental studies focusing on the effects of seismic design and detailing, followed by ones investigating factors such as longitudinal reinforcement ratio, continuous/discontinuous reinforcement, joint details, and influence of precast techniques.

3.3.1 Seismic Design and Detailing
Progressive collapse performance of RC frame structures could be affected by seismic design or seismic detailing. It is worth noting that seismic design differentiates from seismic detailing that the former usually design and reinforce members under the consideration of seismic action, in which the ratio of longitudinal reinforcement and the cross-section dimension is larger in most cases, so progressive collapse performance will be improved without a doubt.

Experiments concerning seismic detailing (Li & Yap, 2011; Lim et al., 2017a; Qian & Li, 2012b; Yu & Tan, 2013a, 2017) usually introduced seismic detailing into structures by intensifying the stirrup spacing at beam ends, providing stirrups at beam–column joints and bending hoop stirrups with 135-degree rather than 90-degree, extra longitudinal reinforcement is also implemented in some cases. All relating experiments are conducted under middle column removal excepting Li and Yap (2011) under corner column removal. Its column removal location could be of influence because CAA and CA cannot be activated under corner column removal. The shear capacity of joints is critical for resisting progressive collapse therein. It is interesting that all researchers of these studies are or were affiliated to Nanyang Technological University, majority of these studies

(Lim et al., 2017a; Yu & Tan, 2013a, 2017) concluded that seismic detailing has only minor or negligible improvement to progressive collapse resistance, while Li and Yap (2011) suggested that transverse reinforcement in joint regions and increase of longitudinal reinforcement ratio are beneficial. However, transverse reinforcement in beam and column ends are insignificant. Also, Qian and Li (2012b) argued that seismic detailing can significantly improve the global behavior of RC frames in resisting progressive collapse in the scenario of exterior column removal. Key variables of beams excepting cross-section, which is not varied in every test, are compared in Tables 2 and 3.

Seismic design, differing from seismic detailing that usually optimizes reinforcement layout based on gravity design, generally leads to larger dimensions and higher steel consumption of structural members as the earthquake action is considered explicitly and quantitatively. One of the classical experiments was conducted by Lew et. al. (2014) in which the progressive collapse performance of intermediate moment frames (IMFs) and special moment frames (SMFs) are investigated on full-scale sub-assemblages. This research verified that similar behavior and failure modes exist between IMF and SMF specimens and seismic acceptance criteria are conservative for progressive collapse design. The IMF test is reproduced by Ahmadi et. al. (2016) on a 3/10 scaled specimen to further investigate the progressive collapse

behavior of IMF sub-assemblages and discrepancies between full-scale and scaled sub-assemblages. Although the number of cracks and ductility of the scaled specimen is lower than the full-scale sub-assemblage, the scaled specimen can reflect its full-scale counterpart's progressive collapse behavior with acceptable accuracy, according to the researchers. Conclusively, most experiments concerning seismic design suggested that progressive collapse of RC frames could be considerably alleviated with seismic design (Almusallam et al., 2017; Choi & Kim, 2011; Lew et al., 2014; Qian & Li, 2013c). This could be explained from three aspects: (1) higher longitudinal reinforcement ratio in beams, which is beneficial in CA (Lew et al., 2014); (2) stirrups and proper anchorage of longitudinal reinforcement in joints preventing the pull-out of rebars before CA is activated (Choi & Kim, 2011); and (3) shorter stirrup spacing at beam ends leading to a higher rotation capacity of plastic hinges that control the development of CA (Almusallam et al., 2017; Lew et al., 2014; Qian & Li, 2013c).

However, Lin et. al. (2017) examined the effects of seismic and progressive collapse design on structural behavior against multiple hazards. Experiment results suggested that progressive collapse design could lead to a strong-beam–weak-column design which is undesirable in seismic design. Moreover, the researchers proposed a novel reinforcement detailing to mitigate this problem (Lin et al., 2019). Another detailing method employing

Table 2 Comparison of variables in experiments investigating seismic detailing.

Cites	Longitudinal reinforcement ratio increase (%)	Stirrup detailing		Stirrup hoop
		Joints	Beam ends	
Li and Yap (2011)	0.96(T) ↑ 0.46(B) ↑	Varied	Varied	Varied
Qian and Li (2012b)	0.42(B) ↑	Varied	Varied	Varied
Yu and Tan (2013a)	0.17(T) ↑	Varied	Varied	Same
Lim et al. (2017a)	Same	Varied	Varied	Same
Yu and Tan (2017)	0.42(T) ↑	Varied	Varied	Same

Table 3 Comparison of variables in experiments investigating seismic design.

Cites	Cross-section area increase (%)	Longitudinal reinforcement ratio increase (%)	Stirrup detailing		Stirrup hoop
			Joints	Beam ends	
Choi and Kim (2011)	17.8–26.7	0.67–0.86(T) 0.28(B)	Varied	Varied	Same
Qian and Li (2013c)	Same	0.60(T) 0.60(B)	Varied	Varied	Varied
Lew et. al. (2014)	36.7	0.26(T) 0.31(B)	Same	Varied	Same
Almusallam et. al. (2017)	Same	Same	Varied	Varied	Same

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kinked rebars is proposed by Feng et. al. (2017) to cooperate seismic and progressive collapse design simultaneously. Still, more studies on the multi-hazard resistance of RC frame structures are awaited.

3.3.2 Geometry and Non-seismic Detailing

Considering the progressive collapse risk in regions with low seismic precautionary intensity requirements, some researchers have also investigated other factors that might affect the progressive collapse resistance of RC frame structures. Tsai and Chang (2015) investigated the influence of beam span-to-depth ratio and stirrup spacing on collapse resistance of RC beam–column subassemblages. The results suggested a negative correlation between the beam span-to-depth ratio and the collapse resistance. Also, it is found that CA will be weakened if the stirrup spacing is increased. Forquin and Chen (2017) studied the influence of several factors on progressive collapse resistance for RC frame structures: the ratio of longitudinal reinforcement, beam height, and boundary condition. Trung et. al. (2019) worked on the influence of discontinuous longitudinal reinforcement, which was followed by Stinger and Orton (2013) on the same issue. Alogla et. al. (2016) tried to improve progressive collapse resistance of RC frame structures by placing additional longitudinal reinforcement at different heights of beams. The above studies indicated that the progressive collapse behavior of structures can be affected by the ratio of longitudinal reinforcement, beam depth, and boundary conditions. The continuous reinforcement certainly has merits at the elastic deformation stage, but it is insignificant in the CA stage.

The rotation capacity of joints is an important index influencing the progressive collapse resistance of RC frame structures (Qian & Li, 2013c; Sasani & Kropelnicki, 2008; Su et al., 2009; Yi et al., 2008; Yu & Tan, 2013a). Based on this agreement, Yu and Tan (2014) tested the effect of three types of joint detailing on progressive

collapse resistance of RC frame structures, as shown in Fig. 5. The experimental results show that the partial hinge method has the most significant effects on improving resistance with comparable reinforcement usage to traditional detailing.

3.3.3 Precast Structures

The precast RC frame structures is a hot research topic recently, and its progressive collapse performance could be inferior to cast-in situ structures due to reinforcement discontinuity at beam–column joints. It is worth noting that precast structures can be classified into wet connections and dry connections. Their structural performance, especially the former, is usually evaluated with cast-in situ structures because of the emulative (or equivalent to cast-in situ) principle, which means the structural performance of precast structure should equivalent to that of a conventionally designed cast-in situ structure, while the latter could be different because of different ductility and resilience performance. Main et .al. (2014) early investigated the progressive collapse behavior of a full-scale SMF in which spandrel beams are connected to columns by dry connections. Kang and Tan (2015, 2017) investigated the progressive collapse performance of precast specimens employing various emulative cast-in situ detailing. The test results show similar resisting mechanisms between precast and cast-in situ specimens. Nimse et. al. (2015) investigated the progressive collapse performance of dry and wet connections. It is reported that the beam–column connection detailing is of significance to the progressive collapse performance of precast structures. However, several experimental studies employing dry connections suggested inferior performances to cast-in situ counterparts (Almusallam et al., 2018; Qian et al., 2020c; Zhou et al., 2019, 2020). Qian et. al. (2019a) suggested that the progressive collapse performance of precast structures with dry connections is heavily dependent on their connection configurations. Feng et.

Fig. 5 The specimen detailed by partial hinges. Image by courtesy of Yu (Nanyang Technological University).

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al. (2020) performed dynamic and static tests on partially assembled sub-assemblages. The results indicated that its load-resisting mechanisms are consistent under static and dynamic conditions, but its resistance in the CA stage cannot satisfy dynamic demand. More experiments with different precast detailing were presented by Qian and Li (2018), Qian et. al. (2020b), Zhang et. al. (2020), and Qian et. al. (2021). Furthermore, Wang et. al. (2020a, 2020b) investigated the effects of infill walls and lateral restraints on progressive collapse performance of precast structures.

3.3.4 Miscellaneous

Furthermore, Wang et. al. (2016a, 2016b) investigated progressive collapse resistance of RC frames with specially shaped columns. Khorsandnia et. al. (2017) investigated the influence of adding steel fiber. Pham and Tan (2017, 2019) compared the structural behavior of RC sub-assemblages subjected to concentrated and distributed loading. Rashidian et. al. (2016), Du et. al. (2020), and Zhang et. al. (2020) studied the effect of out-of-plane beams on the progressive collapse behavior of beam–column assemblages. Deng et. al. (2020) studied the effects of high-strength concrete on load-resisting mechanisms, which are found either beneficial or detrimental in different stages.

3.4 Retrofitting

In the present experimental studies, typical retrofitting methods and some of the most representative works by each type are (a) FRP-type materials (Qian & Li, 2013e), (b) Strands or tendons (Kim & Choi, 2015) and, (c) Steel plates or bracings (Qian et al., 2019b). FRP-type materials, e.g., glass fiber-reinforced polymer (GFRP) or carbon fiber-reinforced polymer (CFRP), can be bonded or near-surface-mounted (NSM) to improve the tensile strength of concrete (Feng et al., 2019) or wrapped to improve concrete confinement (Li et al., 2019a). Strands or tendons can improve CA by providing extra axial strength and CAA if tendons are prestressed (Qian et al., 2018b). The effect of steel bracings is similar to infill walls, i.e., providing compressive or tensile struts. Results on RC frame structures suggested that rational retrofitting could considerably increase progressive collapse-resisting capacity at different deformation stages considering characteristics of different retrofitting methods, but the resisting mechanisms are not altered fundamentally. For example, in Qian et. al. (2019b), the steel bracing strengthening is proven effective in increasing the first peak load and initial stiffness of frames in this experimental study; however, it cannot improve CA capacity because braces usually fail before CA is mobilized.

The application prospective of progressive collapse retrofitting needs to be considered with caution. Present studies discussed several directions such as (a) strengthening new structures designed with current codes to achieve more superior progressive collapse performance (Qian & Li, 2019), (b) retrofitting existing out-date structures to meet current progressive collapse requirements (Orton et al., 2009), and, (c) rehabilitating structures after progressive collapse events (Li et al., 2019a). Among all these imagines, retrofitting of existing structures seems to be the most promising since it has been proven meaningful on seismic topics from aspects of practical needs and retrofitting effects. New structures designed with current codes could resolve its progressive collapse concerns at the stage of structural design, i.e., enhancing member size and reinforcement detailing, which could be less costly than retrofitting. Only a few rehabilitation cases have been reported, while its research value still exists if actual needs are proposed continuously.

3.5 Discussions

Essentially, the purpose of all static experiments is to find "alternate load paths" under the assumption that the "column removal" is the result of an isolated local event (the removal of only one column) without joint damage. It is also assumed that every floor behaves independently, and the load path is independent of the threat, of the loading rate, and of structural systems whose distance is far enough from the column removal location horizontally and vertically. More radical simplifications ignored the influence of slabs and infill walls. These assumptions might deviate the static test results from the actual performance of RC frame structures in progressive collapse, but it is an encouraging fact that static test results do unveil the possible existence of alternate path loads, especially the existence of CA in frame beams. This reminds stakeholders that good progressive collapse performance could be reached on RC frame structures at a very low economic cost if the reinforcement could be arranged properly.

4 Dynamic Behavior

The progressive collapse of actual RC frame structures is a dynamic process. Early versions of guidelines (DoD, 2009; GSA, 2003) employed a fixed factor 2.0 to consider dynamic effects in static analysis. However, the accuracy of this value has been questioned due to geometric and material nonlinearities. Some studies believed that 2.0 resulting in over-estimation of dynamic effects (Russell et al., 2015; Tian & Su, 2011), and the range of 1.3–1.5 is considered more realistic (Marchand & Alfawakhiri, 2004; Ruth et al., 2006). It is also worth noting that dynamic factors in some studies were reported greater

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than 2.0 (Orton & Kirby, 2014; Pham & Tan, 2017; Qian & Li, 2012a, 2017a), which will be further discussed in Sect. 4.3. On the other hand, a fixed dynamic factor leads to inconsistency in structural reliability for structures with different safety levels, so an improved algorithm based on ductility is proposed by McKay et. al. (2012) and further employed by DoD 2009 and GSA 2016. However, the algorithm's fidelity has not been validated by sufficient experimental data (Qian & Li, 2015), and the algorithm is considered conservative still. Relevant discussion on deficiencies of current dynamic factors and further elaboration can be found in Qian and Li (2012a), Tsai (2012), Tsai and You (2012), Liu (2013), and Amiri et. al. (2018).

In current progressive collapse experimental studies, actuator loading and gravity loading are generally used for static and dynamic testing. When actuators apply the loads, the tested system can be considered a static equilibrium because the loading rate is generally low. However, when the loads are applied by the gravity of weights and the column removal is triggered suddenly, specimens are in dynamic equilibrium because of the inertial effect, which is the major issue to be addressed when evaluating the dynamic resistance of structures. There are two solutions for dynamic resistance measurements in current experimental practice. The one is to measure the acceleration of the applied weight (Bermejo et al., 2017; Xiao et al., 2015), the other one is to measure the reaction force of specimen supports (Pham & Tan, 2017, 2019). Both methods are not direct and need a conversion to obtain the dynamic resistance.

This section is divided into three parts: Sect. 4.1 mainly discusses experimental studies conducted dynamic tests only; Sect. 4.2 mainly discusses experimental studies conducted both dynamic and static tests. On the one hand, large-dimension specimens and extreme events, which can only be considered in dynamic experiments, are more of a representation to reflect the progressive collapse behavior of actual structures. However, it is generally impossible to conduct static counterparts of large-dimension specimens due to time and cost limitations. On the other hand, studies conducted both dynamic and static tests usually choose sub-assemblages, which can only simulate part of load-resisting mechanisms, but the process of dynamic loading can be simulated straightforwardly. Despite the diversity of test methods, the influence of dynamic magnification factor and damage on load-resisting mechanisms are the main concerns of different progressive collapse studies, so related discussions were presented in Sect. 4.3.

4.1 Dynamic Experiments

The progressive collapse behavior of RC frame structures considering dynamic effects attracted research interests soon after its static counterpart as the prescribed dynamic magnification factor of 2.0 was apparently over-idealized. Su et. al. (2009) conducted a sub-assemblage experiment considering the change of loading rate, and the researchers argued that the effect of loading rate is negligible. Several dynamic experiments on sub-assemblages or planar frames were conducted subsequently (Orton & Kirby, 2014; Qian & Li, 2012a; Tian & Su, 2011). According to experimental results, it is suggested that CAA is still effective under dynamic conditions (Tian & Su, 2011), and the transition of load-resisting mechanisms is accompanied by a significant increase in vertical displacement (Orton & Kirby, 2014). Qian and Li (2012a) proposed two explanations for the absence of the CA in the corner column removal scenario. Besides, researchers proposed several definitions for dynamic-effect-related factors, the dynamic impact factor (DIF-T) proposed by Tian and Su (2011) is the ratio of dynamic restraint moment peak to static restraint moment, the dynamic amplification factor (DAF-O) proposed by Orton and Kirby (2014) is the ratio of dynamic peak response to its dynamic residual response, and the dynamic load increase factor (DLIF-K) proposed by Qian and Li (2012a) is the ratio of static bearing capacity to dynamic bearing capacity. Various definitions result in different change patterns of factors among researchers. The DIF-T decreases with the increase of gravity loads, and the researchers suggested that the dynamic resistance demand of two-span beams will be over-estimated if the elastic stiffness is employed in the analysis. The DAF-O fluctuated around 1.09, but the validity of the experiment is doubtful because all tests were conducted on the same specimen. The DLIF-K is an upper bound of dynamic capacity, and the study suggested that a factor of 2.0 is too conservative.

The progressive collapse experiment on a three-story spatial frame performed by Xiao et. al. (2015) is one of the largest on scale excepting actual buildings by far. In this experiment, column removal was simulated by disabling temporary supports using hydrogen gas cannons. The comparison between experimental results and finite analyses suggested that a dynamic amplification factor of 2.0 predicted a slightly larger displacement, but it is reasonably close to experimental results.

Adam et. al. (2020) carried out a dynamic experiment on a large-dimension RC flat-plate structure designed per Eurocode 2 (Fig. 6), under the corner column removal scenario. Although the specimen employed the flat-plate RC system, the results suggested that alternate paths are provided by beam action and Vierendeel action while the

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Fig. 6 Full-scale flat-plate specimens. Image by courtesy of Adam (Polytechnic University of Valencia).
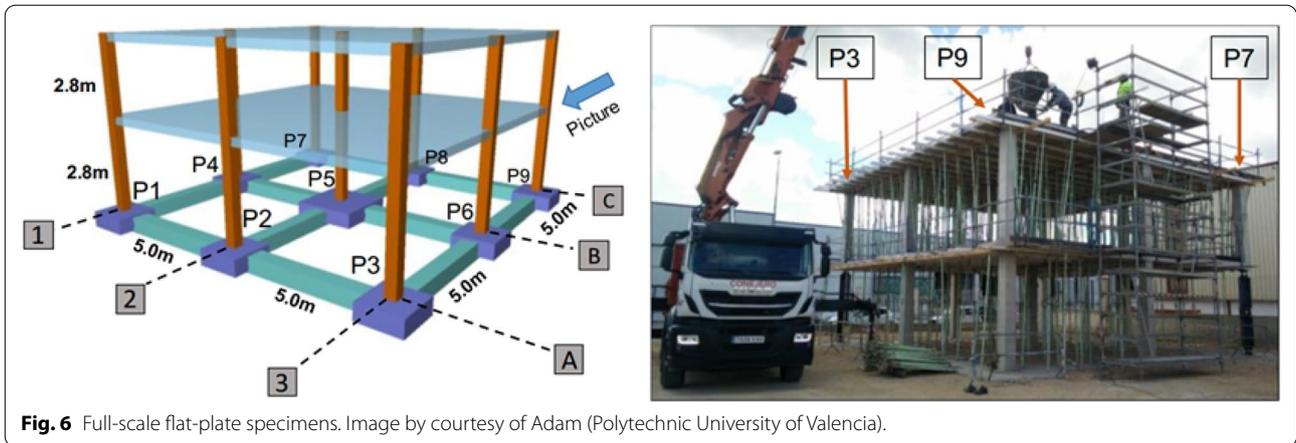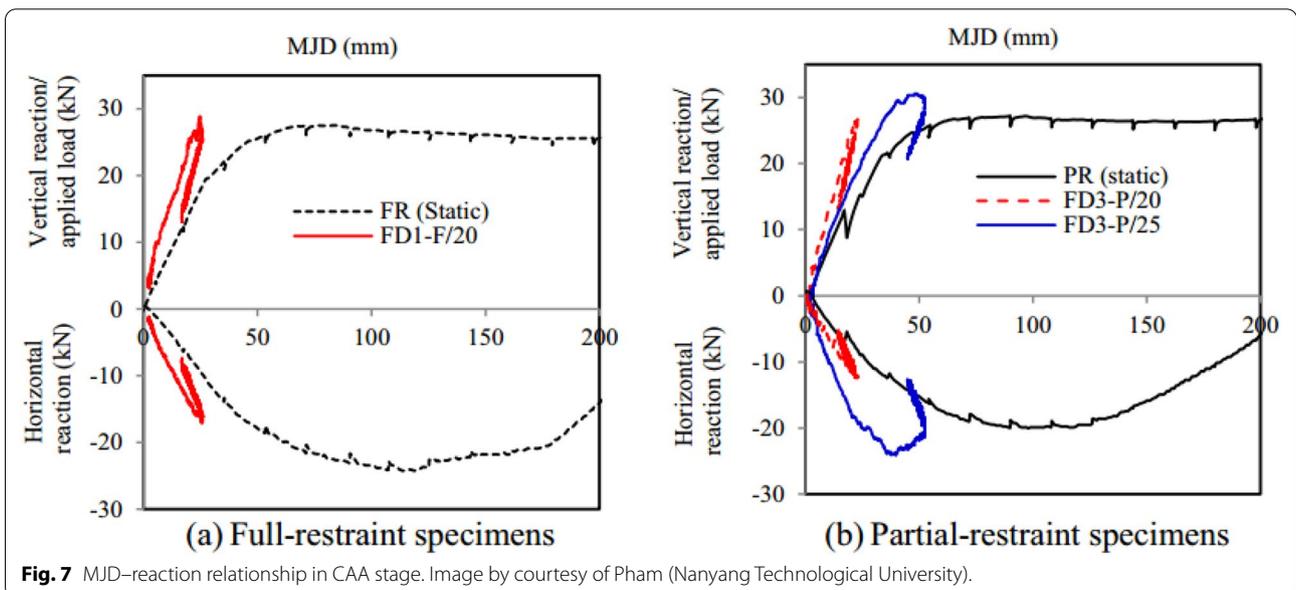
contribution by membrane action of slabs is insignificant. The structure did not collapse after dynamic column removal. Experimenters convinced that a factor of 2.0 could lead to unrealistic evaluation because the dynamic amplification factor (DAF) obtained in the test is only 1.24. Kokot et. al. (2012) also conducted a dynamic experiment on a full-scale flat-plate specimen, and the structure also did not collapse after successive removal of two columns.

Besides, some explosion-related progressive collapse experiments, of which findings are presented in detail in Sect. 5, can also be categorized as dynamic experiments. They can be further divided into near-field explosions and contact explosions.

4.2 Static and Dynamic Collapse Mechanisms
More attention has been paid to the comparison of dynamic and static response differences at the sub-assemblage level in recent years. Qian and Li (2017a) carried out dynamic and static progressive collapse experiments on RC beam–slab–column sub-assemblages, and the results suggested that similarities exist on the failure modes and load-resisting mechanisms of the dynamic and static column removal. However, the CAA weakened or completely disappeared under dynamic conditions, and researchers believed that it is caused by the reduction of initial structural stiffness under dynamic conditions. Pham and Tan (2017, 2019) compared the dynamic and static behavior of RC sub-assemblages subjected to concentrated and distributed loading. The results showed consistency of structural behavior between dynamic and static specimens,

Fig. 7 MJD–reaction relationship in CAA stage. Image by courtesy of Pham (Nanyang Technological University).
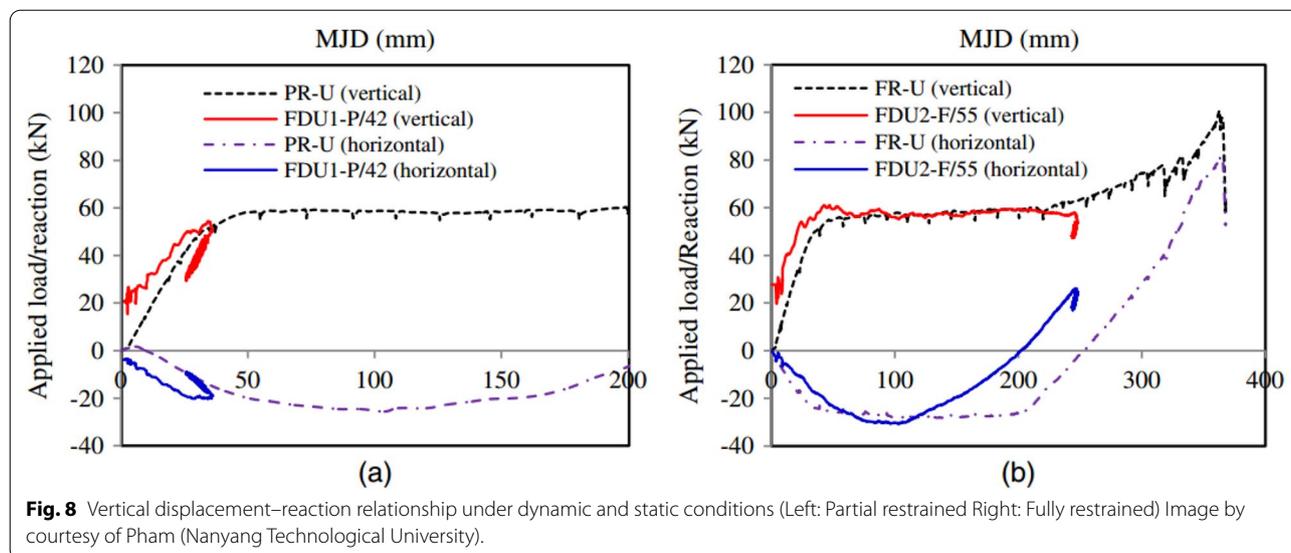
Fig. 8 Vertical displacement–reaction relationship under dynamic and static conditions (Left: Partial restrained Right: Fully restrained) Image by courtesy of Pham (Nanyang Technological University).

and the sudden column removal did not change the failure mode of sub-assemblages. Structures generally exhibited higher stiffness in dynamic tests (as shown in Figs. 7 and 8), while it is noted that the distributed loading seems not favorable for the development of CA.

4.3 Discussion

One of the main purposes of conducting dynamic tests is to study the changing pattern of the dynamic amplification factor, on which existing dynamic experiments have not reached a consensus. This problem is partially ascribing to the fact that the load increase factor (LIF) and dynamic increase factor (DIF) in current guidelines are not experimentally verified nor clearly defined (Adam et al., 2018; Qian & Li, 2015). The physical meaning of the dynamic magnification factor is the increase in the equivalent static load or equivalent static displacement caused by the inertial effect. They are naturally different due to their inherently non-linear characteristics except under the linear SDOF condition. Considering the acceptance criterion of members, it might be more reasonable to research and apply corresponding force-controlled or deformation-controlled factors separately. The deformation-controlled factor can be readily defined as the ratio of dynamic peak displacement to its displacement under the same static loads, and it is measure-friendly. However, the definition and measuring methods of force-controlled factors are much more complicated because the threshold of loads that is enough to cause the progressive collapse of structures under dynamic conditions while remaining structures intact under the same loads in static conditions cannot be obtained by a single dynamic test, which is the main research interest of dynamic studies.

The amount of inertial mass and its release speed are both involved herein.

In several studies, dynamic amplification factors greater than 2 are reported. Qian and Li (2012a) obtained a maximum DLIF (referred to as DLIF-Q for disambiguation hereafter) of 2.16 in their experiments, and Pham and Tan (2017) obtained a maximum DLIF (referred to as DLIF-P for disambiguation hereafter) of 2.22. Both definitions employed the ratio of static bearing capacity to dynamic bearing capacity. Consequently, the above factors represent upper bound points on the performance curve of the dynamic load–displacement relationship if the structure did not collapse. These factors could exceed 2 because they will decrease if the dynamic loads continue to increase. The dynamic amplification factor (DAF-O) defined by Orton and Kirby (2014) is the ratio of peak response (displacement, reaction, strain, etc.) to the residual static response. It was found that the DAF-O of horizontal load and reinforcement strain can reach 4.49, and the researchers believed that the shock effect produced by dynamic loading may contribute to this phenomenon. (Qian & Li, 2017a) also defined a DAF (DAF-Q) as the ratio of the dynamic peak displacement to the static displacement under the same load. The measured DAF-Q for different load levels were 2.5 and 4.5, respectively. Since the DAF-Q is deformation controlled, a DAF-Q greater than 2 could be caused by plastic deformation under dynamic loading.

A deformation-controlled factor greater than 2 is understandable in the plastic stage considering the nature of plastic deformation, but a force-controlled factor greater than 2 is apparently related to the

acceleration of the inertial mass. In static tests, it can be observed that the transition of load-resisting mechanism from CAA to CA is accompanied by a decrease of loading bearing capacity. In dynamic tests, this transition will be manifested by an acceleration change in inertial mass, i.e., a sudden increase of motion velocity. That might be the reason why a dynamic magnification factor could greater than 2.

It is also worth noting that the initial damage was reported in some experiments. Its influence is inevitable, especially in threat-dependent experiments. He (2010) performed a spatial frame dynamic experiment that a bottom corner column was removed by contact explosions. After the explosion, loads from the superstructure distributed with large differences among the remaining corner columns owing to initial damage caused by the explosion. Sasani et. al. (2011) pointed out that explosions would cause initial damage to structures because of air blasts and flying debris. In a contact explosion test conducted by Yu et. al. (2014), initial damage leads to a higher DLAF, and the researchers believed that decoupling the initial damage and the performance of remaining structures is inappropriate. Near-field explosions cause more obvious initial damage because their air blasts affect all surrounding structural members more evenly. A near-field explosions experiment conducted by Woodson and Baylot (1999) indicated that lower-floor slabs and bottom columns were damaged with the same level of severity. An experiment carried out by Gao et. al. (2013) suggested that the beam–column joints and the lower-floor slabs were damaged as severely as the beams and columns, and joints damage preceded the removal of columns. Qian and Li (2017a) indicated that the damage caused by the dynamic response of structures will remarkably decrease the initial stiffness and impair the efficiency of compressive actions, but no relevant experiment phenomenon was reported in other studies. Therefore, the authors agree with the perspective that, on the premise of threat independence, dynamic effects did not introduce new factors that could lead to initial damage.

Although the influence of dynamic effects on initial damage is open to discussion, specific threats lead to initial damage and influence progressive collapse behavior needs to be emphasized. It can be extrapolated that other threats can also cause initial damage to structures, e.g., strength deterioration of reinforcement due to high temperature in fires, downward pull force and out-of-plane deformation due to vehicle impacts, etc. Current progressive collapse design guidelines could lead to unsafe design results because threat-dependent factors are neglected. The following agreement abstracted from present experimental studies can be helpful for future research:

1. A fixed dynamic magnification factor between 1.3 and 1.5 is more reasonable than 2.0 considering the material and geometric nonlinearity, while the ductility-based dynamic magnification factor algorithm needs further experimental and theoretical research.

2. Dynamic effects will not change failure modes of structures because crack patterns in dynamic and static tests are similar, so load-resisting mechanisms based on static analyses are still applicable to dynamic analyses.

3. The structure design always obeys the principle of worst-case load in which the dynamic magnification factor of RC frame structures in progressive collapse design should also choose the largest one, viz. the obtained gravity acceleration maximum when the mass carried by structures is released suddenly and the structure bearing capacity at its lowest point. The experiment conducted by Zhou et. al. (2020) in which specimens sustained intact for 20 min after sudden column removal demonstrated that structures can survive with considerably large displacement. Dynamic magnification factors obtained in this manner can be considered as the maximum value.

4. Threat-dependent dynamic experiments have shown that specific threats can influence the progressive collapse behavior of structures (Gao et al., 2013; Woodson & Baylot, 1999; Yu et al., 2014). Therefore, uncertainties related to the threat-independent assumption need to be eliminated by further studying the dynamic behavior of structures subjected to threat-dependent conditions (Qian et al., 2018a).

5 Threat-Dependent Research

As discussed above, risk could exist in the threat-independent assumption because this approach does not take the effects of external forces on column failure into account, neither consider the column failure process by which alternate load paths are formed. For example, high-temperature effects could simultaneously act on all structural members, and so do actions caused by air-blast explosions. Interpretation on threat-dependent experiments or analyses suggested that damage under threat-dependent scenarios could be more severe than its threat-independent counterparts.

5.1 Explosions

Near-field explosion, which arranges explosives surround the structure, and contact explosion, which embeds explosives in or attaches on the surface of columns, are two methods to conduct column removal in an explosion-related progressive collapse experiment. In terms of the near-field explosions, a 1/4 scaled spatial frame

structure experiment was conducted by Woodson and Baylot (1999) to investigate the influence of different cladding configurations on the impact-resisting capability of RC columns. The results suggested that the cladding (infill wall) can significantly alleviate the damage on slabs because it can reduce the explosion pressure, but it also leads to more severe damages on bottom columns. Gao et. al. (2013) also studied the progressive collapse of spatial frame structures under near-field explosion scenarios. Unfortunately, data acquisition was severely disrupted because the explosion destroyed most of sensors on the structure.

Matthews et. al. (2007) conducted a contact explosion test on a demolish-scheduled two-story frame structure in which a column was removed to assess its dynamic behavior. Monitored data in the test suggested that the structure remained linear elastic after the explosion, while the increased peak axial force in surrounding columns was higher than twice the corresponding steady-state increase, which is beyond the expectation by linear elastic theory and is ascribed to the magnification effect of explosion pressure pulse according to the researchers. He (2010) investigated the influence of sudden column removal by contact explosion on the progressive collapse performance of an RC spatial frame. According to the experiment, contact detonation has a significant influence on the removed column while a minor influence on adjacent slabs and beams. Explosion action caused considerable tensile effects to the superstructure by stretching longitudinal reinforcements in the column, and the risk of structural collapse was increased. Bermejo et. al. (2017) conducted a similar contact detonation experiment on an RC spatial frame, and the structure totally collapsed after the bottom middle column was removed. However, accelerometers in this experiment were also destroyed, so only limited displacement data were acquired. Yu and Tan (2013a), Yu et. al. (2014) studied the influence of contact explosion on an RC sub-assemblage and compared its data with a static experiment. Test results suggested that the structure experienced an uplift force and out-of-plane moment and torsion caused by the impact wave of the explosion. The overall and local crack patterns were similar to static tests.

Besides, several experiments on actual RC buildings were conducted by Sasani et. al. (2007), Sasani and Sagiroglu (2008), Sasani and Sagiroglu (2010), Sasani et. al. (2011), and Keyvani and Sasani (2015) employing the contact explosion to remove single or multiple columns. Tested buildings include the frame (Sasani & Sagiroglu, 2008; Sasani et al., 2007, 2011), frame-shearwall (Sasani & Sagiroglu, 2010), and the flat-plate (Keyvani & Sasani, 2015) structure. No structure collapsed in these experiments, and the structural members basically behaved in the elastic stage (Sasani & Sagiroglu, 2008, 2010). It indicated that the resistance of actual buildings is higher than anticipated due to multiple load-resisting mechanisms. Vertical displacement is mainly caused by the joint rotation, so the researchers suggested that progressive collapse design should focus on the joint anchorage of beam longitudinal reinforcement (Sasani & Sagiroglu, 2008). The uni-directional and bi-directional Vierendeel action are considered to be the main mechanisms providing alternate paths on actual buildings (Sasani & Sagiroglu, 2008, 2010; Sasani et al., 2007, 2011), and the deep beam in the lower floor is also beneficial for load redistribution if the structure is designed with deep beams (Sasani et al., 2011). It is also worth noting that the axial force in upper columns experienced an apparent decrease after bottom columns were removed, and axial tension was recorded during column removal (Sasani et al., 2007).

Experiments by Sasani et al. seem to indicate that actual buildings are considerably robust to progressive collapse because of multiple load-resisting mechanisms, which can delay the failure of critical members and provide multiple paths for load redistribution. However, progressive collapse design and evaluation of structures cannot comprehensively utilize these multiple mechanisms with large uncertainties. Since few data were obtained at the mechanism level during explosion experiments of actual buildings, it is difficult to quantify the effect and interaction of multiple load-resisting mechanisms. Underlying connections in the experimental results between sub-assemblages and actual buildings should be paid more attention.

Explosion-related progressive collapse experiments revealed several phenomena that worth further research. First, target columns in most experiments were not removed completely, and damage of columns concentrated at regions where the explosive was placed, which is similar to the damage of columns under seismic action. In this case, the remaining columns could touch the ground, so CA would not appear. Second, the remaining longitudinal reinforcement connecting columns and the ground could increase the damp of structures. Third, the process of explosions could cause initial damage to other members and alternate load paths. As discussed in Sect. 3.4, initial damage might affect or destroy alternate load paths.

5.2 Fires
Another threat that could lead to the progressive collapse of building structures is fires. The safety of steel structures under fires has aroused extensive attention, but research on RC structures is relatively few. The risk of collapse exists on RC structures if subjected to fires, as demonstrated in the 113 Hengyang Fire Accident. The

experiment conducted by Li et. al. (2018) suggested significant discrepancies of mechanical behavior between beam–column joints before, during, and after fires. In this study, reinforcement detailing conforming to ACI 318-14 cannot prevent progressive collapse if the structure is exposed to fire for 2 h, and CA cannot be motivated on beam–column joints in fires. Li et. al. (2019b) then studied the influence of different reinforcement detailing on rotation capability of joints before and after fires. The experimental results suggested that partially debonded bottom rebars were the most effective detailing in improving the rotation capability of joints before and after fires. Post-fire specimens developed more cracks and flexural deformation compared to pre-fire specimens, so it exhibited relatively low bearing capability in beam action and CAA while higher bearing capability in CA.

Furthermore, Kamath et. al. (2015) carried out a pushover experiment on a full-scale RC spatial frame that experienced seismic action and fire. The results demonstrated that slabs were most severely damaged in fires, with a large area of concrete spalling from the downward face. Data from the pushover experiment suggested degeneration of lateral strength and stiffness of the structure after seismic action and fire, but the tested frame did not collapse with 200 mm of lateral deformation.

The above experiments provided basic data and information to evaluate the progressive collapse risk of RC frame structures subjected to fire. Nevertheless, the experimental study is still lacking on some critical issues, for example, axial bearing capacity of RC columns in fires, the influence of different temperature fields on RC columns, and residual capacity evaluation of post-fire columns.

5.3 Lateral Impact

In terms of experimental studies on progressive collapse resistance of building structures under lateral impact loading, previous studies usually employed so-called nominal column removal to simulate the sudden failure of columns, e.g., the RC joint sub-assemblage experiment by Qian and Li (2012a) and the RC frame experiment by Xiao et. al. (2015). The nominal column removal takes dynamic effects of suddenly imposed gravity loads into consideration. However, the pull-down force caused by longitudinal reinforcement of removed columns is not considered because the monolithically poured concrete and reinforcement are neglected. Several numerical studies paid attention to the influence of column removal on superstructures, but no relevant experiment was reported.

Progressive collapse accidents caused by the lateral impact is relatively rare on RC frame structures

(Gurbuz et al., 2019), but it happens on bridge columns or piers sometimes because of the truck or ship collision, as reported in Buth et. al. (2010), Chen et. al. (2015), Sharma et. al. (2015), and Wan et. al. (2019). Most impact-related studies focused on the impact-resisting performance of columns, while few studies investigated impact performance at the structural level. Numerical analyses (Gu et al., 2014; Luo et al., 2019) suggested that the threat-independent assumption is unrealistic in reflecting progressive collapse behavior of structures subjected to actual lateral impact loads. Some latest experimental studies also indicated that failure patterns of RC columns could influence subsequent progressive collapse behavior of structures (Fig. 9). The causes of this problem can be summarized in the following aspects: first, the lateral force transmitted from the removed column to the structure, which weakens structural robustness by causing initial lateral displacement and joint damage, has not been considered in the process of nominal column removal. Secondly, columns generate a pull-down force to structures in the process of being impacted, and

Fig. 9 The failure pattern of axially loaded column subjected to lateral impact. Image by courtesy of Sun (Hunan University).

this pull-down force cannot be simulated in a nominal column removal. Lastly, the possibility of multi-column removal exists in actual impact accidents (Gurbuz et al., 2019; Kang & Kim, 2015). The above-mentioned factors lead to a significant difference between the results obtained from impact-related numerical studies and the results from nominal column removal studies, so further investigation is still needed.

5.4 Earthquakes
Numerous examples of earthquake damage have shown that the collapse of frame structures results in serious losses of life and property. Some researchers studied the mechanism of earthquake collapse by cyclic loading tests or shake table tests. (Xie, 2015) investigated the collapse behavior of RC planar frames under the seismic action, in which the horizontal cyclic displacement was quasi-statically applied by actuators. It is illustrated that the structure collapsed because a bottom middle column failed after the concrete crush at the lower part of the column. Stavridis et. al. (2012) conducted a shake table test on a three-story planar frame with infill walls. The results indicated that the soft-story mechanism, which formed after the development of severe diagonal cracks at bottom columns, is responsible for the failure of the structure. Infill walls can alleviate seismic damage to frame structures. Nevertheless, the researchers argued that infill walls are usually missing in some critical positions of actual buildings, e.g., the first floor, which could lead to significant impairment of earthquake-resisting performance. Similarly, Kim et. al. (2012) also conducted shake table tests on two RC specimens with identical parameters, except one was strengthened by polyester fiber sheets and belts. In addition to results regarding strengthening, the test also reported damage concentration and larger lateral displacement at bottom columns comparing with other members and other floors.

Despite experimental studies on structural collapse mechanisms under seismic action, a foreseeable progressive collapse scenario is that frame structures are damaged by seismic action. The progressive collapse is triggered by gravity loads and seismic action simultaneously after the most severely damaged columns quit bearing loads. Studies on this issue have not been reported yet.

5.5 Discussion
As reviewed above, progressive collapse studies related to threat-dependent and multi-hazard problems should be paid attention to and extensively investigated. Before that, two prerequisites on which have profound influence are suggested to be met by the authors to facilitate further research of threat-dependent problems.

In terms of theoretical studies, establishing the relationship between input impact energy and damage state of columns is of guidance to experiment design and codification of progressive collapse precaution standard on structures subjected to impact action. Reference can be found in analysis framework (Kishi & Mikami, 2012; Kishi et al., 2001, 2002; Yi et al., 2016) that correlated the relationship between impact energy of columns and its mid-span displacement. However, internal and external factors of RC columns could be influential to its impact-resisting performance (Demartino et al., 2017). Experimental results demonstrated that internal factors like boundary conditions, configurations of transverse reinforcement, and external factors like input energy and impact point location can affect the impact-resisting capability of RC columns. It is showed by actual accidents that impact accidents caused by heavy trucks are more likely to occur at the lower part of bridge columns and cause shear damage to columns (Buth et al., 2010), and calculation methods based on the flexural capability of beams are hardly applicable under this condition (Kishi & Mikami, 2012).

Another potential problem with threat-dependent experiments is the reliability of sensors (Bermejo et al., 2017; Gao et al., 2013; Kamath et al., 2015). Although it is not a quite common problem in impact experiments of RC members, and the influence of impact loading could be relatively low in impact experiments, the redundancy design of measuring equipment in all threat-dependent experiments is necessary considering the cost of specimens is substantially higher than the cost of sensors in most cases.

In summary, threat-dependent progressive collapse experimental studies need further investigation. Substantial evidence of influence of diverse threats on structural robustness is still lacking, so difficulties still exist in performing threat-dependent-based progressive collapse design. The rationality of threat-independent assumption needs to be re-evaluated after sufficient experimental data is obtained on threat-dependent studies. A possible methodology is that the influence of specific threats can be integrated into the conventional threat-independent design by considering strength reducing factors or ignoring contribution from some radical load-resisting mechanisms.

6 Conclusions
Concerns in the structural engineering community on progressive collapse increased after influential accidents like the Ronan Point accident and the 9/11 Attack. Most experimental studies on RC structures were reported in the last decade, in which profound findings have been

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revealed on resisting mechanisms, dynamic characteristics, and influencing factors of RC structures subjected to progressive collapse. The goal of this paper is to summarize these diverse works to facilitate future research. On this basis, the following conclusions are derived from different aspects.

a. Hot topics: Load-resisting mechanisms, either primary or secondary, are the principal concern of any study relating to progressive collapse. Researchers also concern about the column removal scenarios because the motivation of load-resisting mechanisms depends on boundary conditions. Dynamic performance is another domain long receiving considerable attention since the progressive collapse process is naturally dynamic. Since traditional topics have been comprehensively investigated, research interests in precast structures and retrofitting techniques employing novel materials earned a considerable rise.

b. Load-resisting mechanisms: RC frame structures resist progressive collapse at different deformation stages through primary actions like beam action, compressive arch action, and catenary action. Numerous experiments on sub-assemblages have described the role of these primary actions as resisting mechanisms. Experimental results also suggested membrane actions of slabs and infill wall effects could be important to progressive collapse resistance of structures. Furthermore, experiments on detonation-scheduled buildings indicated that actual buildings are more robust than anticipated, which could be ascribed to the interaction of multiple resisting mechanisms.

c. High-risk column removal scenarios: Load-resisting mechanisms of RC frame structures have wide discrepancies in different column removal scenarios. Mechanisms like CAA and CA require strong lateral stiffness to be motivated. Scenarios like column removal of the corner, penultimate corner, and penultimate external face a higher risk of progressive collapse for the absence of essential mechanisms.

d. Influence of design parameters: The seismic detailing and the seismic design need to be considered differently in progressive collapse design. Generally speaking, the seismic detailing has no significant improvement on progressive collapse performance, while the seismic design will improve progressive collapse performance of structures because it increases the plastic rotation capability of beam ends and prevents the failure of beam–column joints. However, progressive collapse design could be undesirable to seismic performance since the strong-column–weak-beam and strong-joint–weak-member principles are disobeyed

if beams are over-strengthened. Influence of several factors has been investigated, in which the rotation capacity of plastic hinges is essential and fundamental.

e. Dynamic effects: The dynamic effects are the main concern of progressive collapse dynamic experiments. Considering a factor of 2.0 is over-conservative, a factor between 1.3 and 1.5 might be more reasonable for estimation. Dynamic effects have no apparent influence on resisting mechanisms and failure modes of structures, suggesting load-resisting mechanisms identified on static analyses are still applicable to dynamic analyses.

f. Progressive collapse caused by explosions or earthquakes: Load-resisting mechanisms in explosions and earthquakes could be jeopardized because experimental observation suggested that corresponding actions damage structures holistically. Adjacent members are vulnerable in near-field or contact explosions, and infill walls could aggravate damage because of the involvement of explosion pulses. In earthquakes, damage and lateral displacement concentrate at bottom structural members. Therefore, the threat-independent assumption could be flawed when evaluating structures subjected to extreme events. The progressive collapse triggered by earthquakes could be considered a combined consequence of seismic and gravitational effects on the damaged structure after structural columns were seismically damaged. This issue has not been investigated sufficiently since relatively few experimental studies were reported.

7 Recommendations and Future Needs

a. Research targets: More emphasis should be put on progressive collapse research of large public buildings like governmental centers, commercial complexes, and transportation hubs in which beam spans are larger than residential buildings so that two-span beams after column removal might fail to form alternate load paths. Also, past cases suggested a higher risk of malicious attacks on public buildings far than residential buildings.

b. Correlations between experiments and design: Experimental studies should aim at more comprehensive design methods for progressive collapse. What needs further investigation is the correlation between experimental findings and design methods, for example, the influence of infill walls and slabs, and strategies resisting progressive collapse under high-risk and multiple column removal scenarios.

c. Dynamic effects: Dynamic effects should be investigated under unified definitions with clear physical means. The calculation methods of DIF and LIF in current guidelines should also be validated or verified by experimental research. Because the progressive collapse of RC structures is featured by dynamic and non-linear effects, corresponding force-controlled or deformation-controlled magnification factors should be developed according to the acceptance criterion of members. A clear change pattern of dynamic magnification factors might be established in the future based on these works.

d. Retrofitting: Retrofitting existing structures designed with obsolete standards needs further investigation since its engineering needs could be high but relevant research is relatively few. At the same time, retrofitting needs to be quantified since its purpose is to meet current requirements. It is also worth noting that the applicability and durability of retrofitting are of importance to engineering practice.

e. Threat dependent: Several threat-dependent analyses or experiments have indicated potential problems of the threat-independent assumption. Current progressive collapse codes and design guidelines basically ignored the influence of threats, and relevant experiments and theories are still lacking. The influence of threats on the progressive collapse behavior of structures can be divide into two aspects, load action and structural resistance. Therefore, threats could be considered in conventional progressive collapse design by load action factors and structural resistance factors if threat-dependent studies are adequately developed.

Supplementary Information

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Additional file 1: Appendix S1. A detailed record of experimental studies is archived at https://drive.google.com/file/d/1o12rucAMyje8O9vA1uGCt95xCSuDdLEk/view?usp=sharing.

Authors' contributions
W-JY provided the basic idea and critically revised this article. FY performed the literature search, data analysis, and draft writing. YZ contributed to the further literature search and revising. All authors read and approved the final manuscript.

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Declarations

Competing interests
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