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Experimental studies on the progressive collapse of building structures: A review and discussion on dynamic column removal techniques

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ABSTRACT

Dynamic progressive collapse tests are becoming more and more popular in recent years since this approach captures the real structural behavior more robustly, and progressive collapse response more accurately. The results of dynamic tests are of great importance for defining computational models and improving current codes and guidelines. Even for static tests and simulations, the dynamic effects should be indirectly considered, namely by including the dynamic amplification factors. The adopted dynamic column removal approach is the most important and challenging aspect of the dynamic progressive collapse tests. While several methods for dynamic column removal have already been suggested and implemented, a comprehensive discussion of the techniques is missing. In this regard, a comprehensive review of the available literature is first presented. Current experimental techniques for dynamic column removal are categorized into three main groups, i.e., quick-release device, dummy column, and explosion technique, and the underlying concepts and applied methodologies are compared and contrasted. Finally, future needs are highlighted and possible improvements for the current methodologies are also discussed.

1. Introduction

Structural collapse is the biggest fear of structural engineers. Among the different possible collapse modes, progressive collapse, in which an initial local failure leads to a total or disproportionately large collapse [1], is responsible for the vast majority of recent tragic incidents. Understanding the progressive collapse response of a structural system can be very complicated since dynamic and nonlinear effects are always included in the collapse mechanisms. However, huge efforts have been devoted to progressive collapse and structural robustness after 9/11 events, and there is ongoing progress in understanding the phenomenon and methods to analyze, control and prevent it. The major findings are listed and discussed in [2–7].

The experimental study is the most effective and reliable method to investigate structural failure problems. However, dynamic progressive collapse tests are not only expensive, time-consuming and dangerous, but also inherently complicated and rarely straightforward. This is the reason why most of the campaigns on progressive collapse do not work in this way. The results of quasi-static tests, in which the test is performed on an already-damaged assembly, dominate our current knowledge of structural performance in progressive collapse scenarios. Nevertheless, nonlinear dynamic behavior is the inherent nature of any system in progressive collapse scenarios, and the quasi-static studies are only an estimation of the governing physics. It should be mentioned that the results of dynamic tests are of great value even in nonlinear static simulations. Because dynamic amplification factors (DAFs) are expressed in guidelines and codes in a very general framework and application of the code-based DAFs may lead to an underestimation or overestimation of structural responses depending on the building configuration and/or initial failure location [8]. Therefore, a deep focus on dynamic progressive collapse tests is necessary, since there is not a unique and well-accepted method for dynamic column removal, and different researchers have adopted different innovative methods to deal with it. While terms like sudden, abrupt, instantaneous, etc., are used in the available literature, the term "dynamic" is preferred herein, since it captures the inherent characteristics in a more general way. As discussed later in Section 2, column removal time is one of the main parameters that governs the dynamics of the system, and it is greatly advantageous if the column removal devices can monitor, control and adjust this parameter.

Researchers, being human, are subjected to bias and predisposition toward subjects of their studies. The tendency to overestimate our ability and knowledge is highlighted, following the Dunning–Kruger effect [9]. Inexperienced researchers, often consider the experimental procedures straightforward [10]. It is argued that many mistakes could

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be avoided if the aim and scope of the experimental programs are initially articulated and the experimental procedure is deliberately reflected upon [10]. Scientists are not immune to biases even regarding the published studies, especially when it comes to their own work [11]. In structural engineering realm, it is not uncommon to encounter experimental setups that fail to capture the true properties of the subject under study, and/or the obtained experimental results are generalized without considering (or even understanding) the inherent limitations of the adopted test configurations. In this regard, reviewing and revisiting the test procedures are always insightful.

This review paper, for the first time, reports a comprehensive survey, deep discussion and possible improvement of the available literature on dynamic column removal techniques in experimental progressive collapse studies. The paper categorizes and discusses these methods. The adopted categorization of the reported techniques sheds light on the basic concepts and opens a window for possible future alternatives and/or improvement of the existing ones. The advantages and pitfalls of each approach are highlighted. Limitations of each concept, according to the representing structure, are discussed. New theories and novel techniques are seldom born in the void. Therefore, after a comprehensive review, future needs are highlighted and achievable enhancements in the current methodology are also suggested.

2. Dynamic column removal techniques

The available literature on experimental dynamic column removal techniques is classified into three groups. The adopted categorization policy applied to both build-on-purpose specimens and existing buildings, as well as to different constructional materials, namely reinforced concrete and steel. Since similar techniques have been applied to the structures and substructure models with different constructional materials, more distinguishing features are ignored herein and, instead, the analogy in column removal approach is stressed. Therefore, the main emphasis is put on the basic concepts for dynamic column removal and not on the structures that are subjected to it. In this regard, three basic classes for dynamic column removal, i.e., quick-release device (Section 2.1), dummy column (Section 2.2) and explosion techniques (Section 2.3), are extracted from the available experimental literature. The general aspects of the test are discussed herein, while the next three subsections are devoted to the aforementioned dynamic column removal techniques. Fig. 1 summarizes the overall classifications that were used in this study.

The majority of the reported experimental programs are performed on double-span beams or substructures. It should be noted that the real structural behavior in column removal scenario can only be captured in a 3D multi-story multi-span specimen including slabs and infill walls [4,5]. In 2D frames and substructure specimens, some aspects of real structural behavior in term of mass distribution and load transferring mechanisms cannot be completely and accurately apprehended [8]. Therefore, special measures should be taken to control these effects. For example, extra weights in the form of adding masses on the slab and/or hanging weights on the beam are usually applied to represent the real dead and live loads usually based on the code recommendations for dynamic analysis [12,13]. The added mass can be in the form of concrete blocks, steel sheets, baskets full of sand, etc. Out-of-plane support systems, especially in substructure specimens, are usually utilized to guarantee frame movement only in the vertical in-plane direction. As highlighted in [14], load resisting mechanisms of each floor in a multi-story frame is different. This fact should be carefully considered when a substructures model is adopted.

Because experimental studies on dynamic column removal usually involve several structural members, especially when multi-story models are considered, a scaled-down model is widely adopted in experimental studies to overcome space, cost and time limitations. The scale factors of 1/8 [15], 1/4 [16–18], 1/3 [19–21], and 1/2 [22] are frequently reported for dynamic progressive collapse tests. It is well-known that the smaller the specimen, the more dominant the size effect. However, the scaling effects involving the dynamics of column removal response have not been clearly highlighted since the geometrical, mechanical, or dynamic scaling relationships are different. Details like the scaling at material level, namely aggregate in concrete, are not well-documented, too. Based on some studies the size effect would not have a significant impact on structural response under progressive collapse scenarios [20], since the expected dominant failure modes involved flexure and catenary action. However, the scaling effects may vary across various constructional materials when subjected to different loading conditions. Size effect in normal-, high-strength, fiber-reinforced and prestressed concrete, are reported and discussed in [23–25]. Based on some studies [24], the size effect represents a nominal strength reduction of about 30% to 35% even in flexure. As mentioned and discussed in [17,18] testing scaled-down timber structures must be performed with caution, as the strength of a timber element is known to be sensitive to the size, and higher capacities, up to 20%, may be expected. Therefore, when conducting tests on the scaled specimens, it is crucial to carefully consider the size effects and clearly highlight and report any simplifications and assumptions made during the process.

In dynamic column removal tests, a series of linear variable deformation transducers (LVDTs), load cells, accelerometers, strain gauges, etc., are usually installed both internally and externally to monitor the response of the system and local behavior of the specimens [26]. The different instrumental setups reflect the need of the researchers for the required experimental data, say stresses, displacements, internal forces, reaction forces, etc. Load cells are usually installed in column removal devices, namely above the quick-release device (see Section 2.1) or below the dummy columns (see Section 2.2). The vertical displacement at the column removal point is the main output of the dynamic column removal tests. Therefore, the time-history of vertical displacement is of great interest and is usually reported in the available literature. Laser is sometimes used to measure the vertical deflection, or, alternatively, a high-speed camera or LVDT [27], or digital image correlation and low-speed video cameras can serve this purpose. In some cases, ancillary structures are used to facilitate the measurement of the absolute vertical displacements of the column removal point as reported in [28]. Safety columns, located several tens of centimeters below the first floor, can be used in order to avoid a total collapse. Besides, forces in the beams and columns, before and after removal, are usually monitored. Strains, either in critical points like reinforcement bars in RC or connections in steel specimens can be measured quantities. Moreover, strain outputs for the calculation of other parameters, like removal time, are also considered. Figs. 2 and 3 illustrate two configurations for instrumentation.

It should be noted that the involved collapse-resisting mechanisms (flexural, arch action, catenary action, etc.) affect the instrumentation type and pattern. Collapse-resisting mechanisms are related to the amount of vertical displacement in column removal point. Therefore, having an estimation of the structural behavior in column removal scenarios is very insightful in designing the experimental plan. Simulation using advanced finite element packages can serve this purpose perfectly. However, considering the expensive and time-consuming nature of this approach, simplified methods, like what was reported in [31], provide essential insights for instrumentation.

According to Progressive collapse guidelines and codes, it is preferable to remove the column instantaneously, and the duration for removal must be less than one-tenth of the period associated with the structural response mode for the vertical motion of the bays above the removed column [12,13]. Alternatively, column removal time is related to the acting threat and the nature of the initial failure. In other words, while instantaneous column removal always leads to a larger structural response, for a realistic test, the real situation should be considered. In any case, to capture the full dynamic effects, the aforenamed code-based limit is essential. However, the necessity of fully dynamic column removal is related to the aim and scope of the

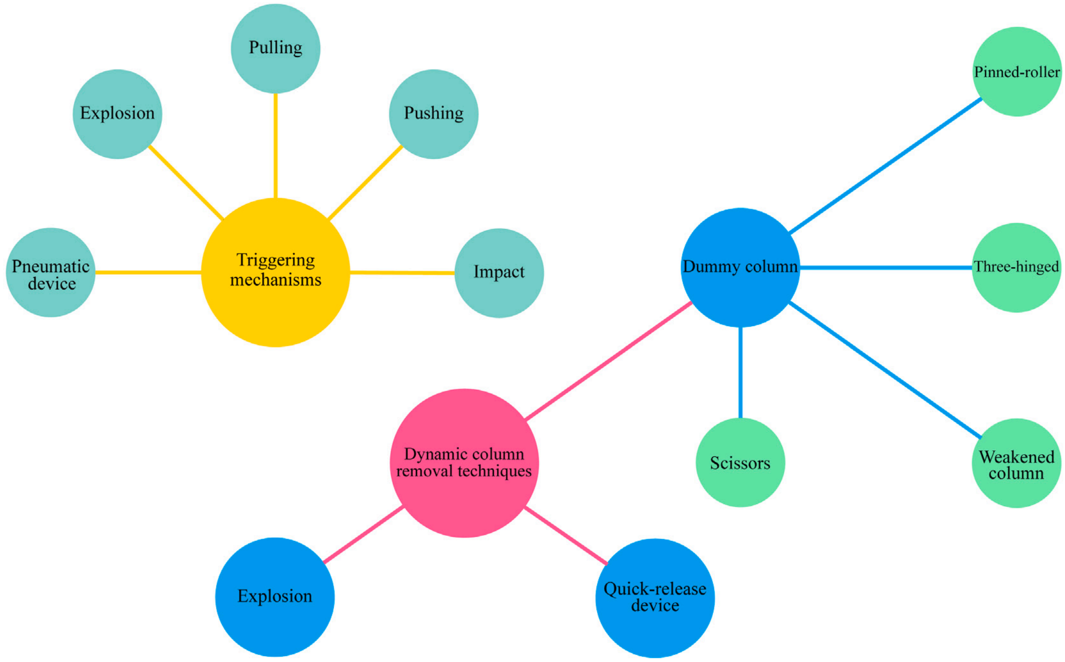


Fig. 1. A general view of dynamic column removal techniques and triggering mechanisms.

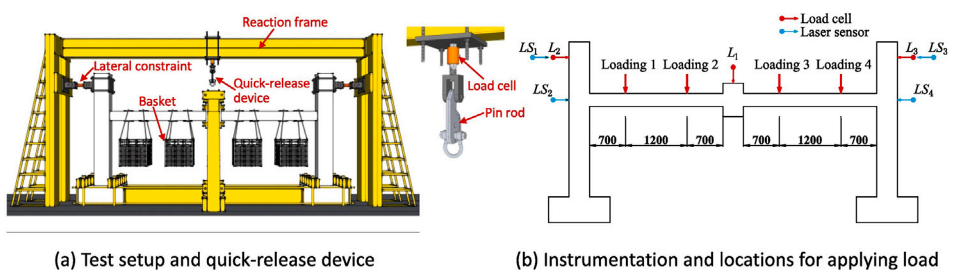


Fig. 2. Instrumentation for dynamic column removal test, as reported in [29]. Steel baskets were installed to describe gravity loads.

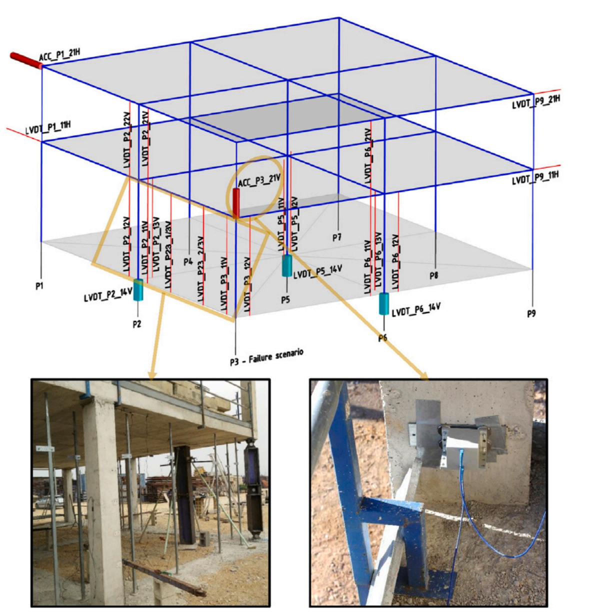


Fig. 3. Instrumentation in dynamic column removal test as reported in [30]; positions of vertical LVDTs and accelerometers in structural scheme (top), collapsible column and safety column in test setup (bottom left) and a close view of an accelerometer (bottom right).

experimental program. For example, if the test represents a column loss due to low-speed impact, the column removal in a certain period of time is favorable compared with abrupt column removal. In any case, the column removal device should monitor and control this time. The limitations and possible improvements regarding column removal time are highlighted in the next sections. Table 1 lists the reported column removal times based on available literature for quick-release device and dummy column concepts. For explosion approach, the column removal time is not well-documented. It should also be noted that the term “column removal time” is used for all approaches, mainly for dummy column method, but when a quick-release device method is adopted “release time” is more favorable. However, in this paper the term “column removal time” is used for all methods, since it addresses the main concept clearly.

2.1. Quick-release device

Quick-release device refers to any tensioning device that supports the beneath slab/beam and can release suddenly to simulate the dynamic column removal. Examples and details of quick-release devices are presented in Figs. 4 to 6. A triggering mechanism is needed for any quick-release device to start releasing and simulating dynamic column removal. A load cell (see Fig. 4) is usually placed in series with the quick-release device to measure the initial axial force [22,50]. Compared to the dummy column, which basically is a column with a releasing mechanism, a quick-release device is essentially a “cable” with a releasing mechanism.

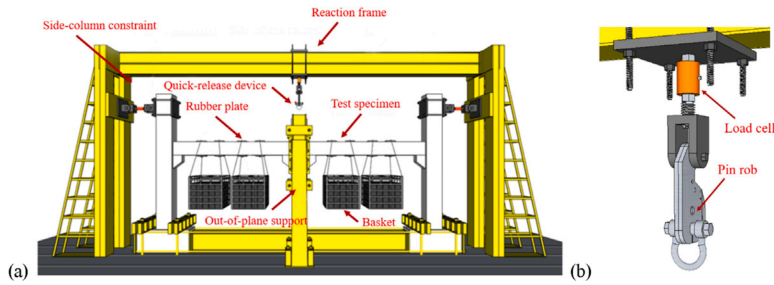


Fig. 4. Dynamic column removal test setup using the quick-release device: (a) boundary conditions and (b) quick-release device, as reported in [22,29].

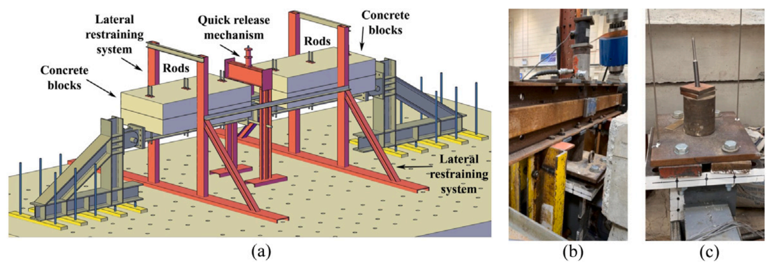


Fig. 5. Dynamic column removal test setup using the quick-release device: (a) overall configuration, (b) quick release mechanism before failure, and (c) quick-release mechanism after failure, as reported in [50].

Table 1
Examples of column removal time (CRT) in milliseconds for different techniques.

Quick-release device		Dummy column concepts	
Author	CRT (ms)	Author	CRT (ms)
Cheng et al. [17]	3	Kai & Li [19]	8 & 12
Cheng et al. [18]	22–70	Qian and Li [26]	20
Pham and Tan [20]	2–25	Li et al. [32]	3 & 3.5
Yang et al. [21]	30	Qian et al. [33]	9–11
Zhou et al. [22]	20–30	Qian and Li [34]	5–7.5
Feng et al. [29]	17–38	Qian et al. [35]	5 & 8
Zhao et al. [36]	60	Han et al. [37]	3.5
Liu et al. [38]	50–80	Peng et al. [39]	12 & 13
Pham and Tan [40]	49–85	Cuong et al. [41]	10
Zhao et al. [42]	14–20	Qian and Li [43]	3-5
Tian and Su [44]	8	Peng et al. [45]	7.4
Liu et al. [46]	30	Zhang et al. [47]	21–69
		Russell et al. [48]	33.7–57
		Buitrago et al. [49]	70

The triggering can be performed by hand or by an electromechanical device. While not widely reported, electromagnetic approaches like the ones suggested in [36] for member-breaking devices in truss structure, can potentially be used as quick-release devices for dynamic column removal in a frame assembly. However, the triggering mechanism in available literature usually includes a rope attached to the handle (see Fig. 6), allowing safe operation under laboratory conditions by yanking the rope away from the test specimens [17,18,20,21,38,40,42]. Alternatively, based on the configuration of the experimental setup, a hanger may be manually knocked off by a hammer to simulate the sudden loss scenario [51]. Burning the string support to trigger the gravitational-induced dynamic effects is also reported in [52].

Column removal time is an important issue in any column removal test (see Table 1). In quick-release devices, the column removal time is actually related to the triggering mechanism. When approaches like “rope yanking” are adopted, the column removal time is not fully controllable. Because, as mentioned and discussed in [22], the release time is affected by the weight of applied loads, as well as the human-controlled triggering device. However, the removal time can be in terms of milliseconds. For example, 8 ms in [44], 20–30 ms in [22], 30 ms in [46] and 17–38 ms in [29] were observed. Therefore, it can be considered as “dynamic” column loss, and moreover, such short times are usually but not necessarily (for example see [46]) less than 10% of the natural period of specimens and thereby enabled the simulation of fully dynamic tests as recommended by progressive collapse guidelines [12,13]. In such an assessment, absolute numbers cannot be suggested, since the natural period is related to the structural assembly. Moreover, generalization to real structures should also be avoided, since in the lab, as mentioned before in this section, usually a substructure model is considered. In the experimental programs, strain gauges can be installed onto the hook of the removed column to determine the load release time when the specimen was released from the initial conditions [38]. Alternatively, other sensors can be used for this purpose. It should be noticed that all the recordings of LVDTs and strain gauges should be initialized to zero before column removal [38].

2.2. Dummy column concepts

A dummy column, or collapsible column, is herein referred to as any temporary (vertically compressed) supports substituting the original structural column (or developed by modification of the actual structural column) and can be released via different mechanisms to mimic dynamic column loss. In the published literature, other terms, namely temporary column, instantaneous column removal device, etc., are also used referring to this configuration. However, the term “dummy” is preferred herein since it points to the underlying concepts, i.e., collapsibility and lack of real initial condition, more clearly. While suggested and used in different shapes and configurations, the basic underlying characteristics are very similar. The dummy column includes a triggering mechanism that allows dynamic column removal. Fig. 7 illustrates an example of the dummy column concept in a steel frame assembly [32]. Fig. 8 shows the details of the dummy column design and installation, as reported in [30]. Herein, the available literature on dummy columns in terms of the shape, boundary conditions and triggering mechanisms are reviewed and discussed.

2.2.1. Shape and boundary conditions

Dummy columns are designed in different shapes and configurations based on the constructional materials, lab limitations and scope of the study. Therefore, the basic similarity between different approaches is only in the underlying concept. When a dummy column is in steel, that

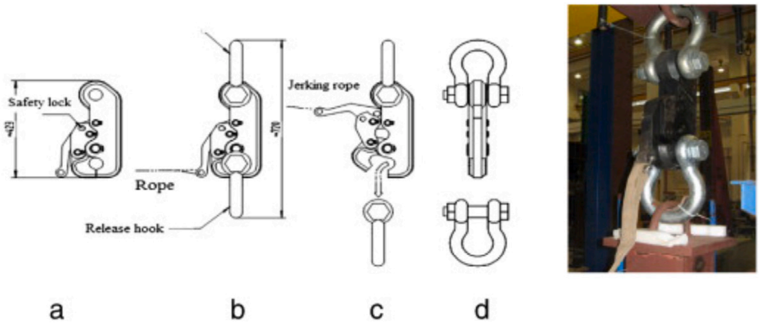


Fig. 6. Quick-release mechanism to simulate sudden column removal scenario, as reported in [38].

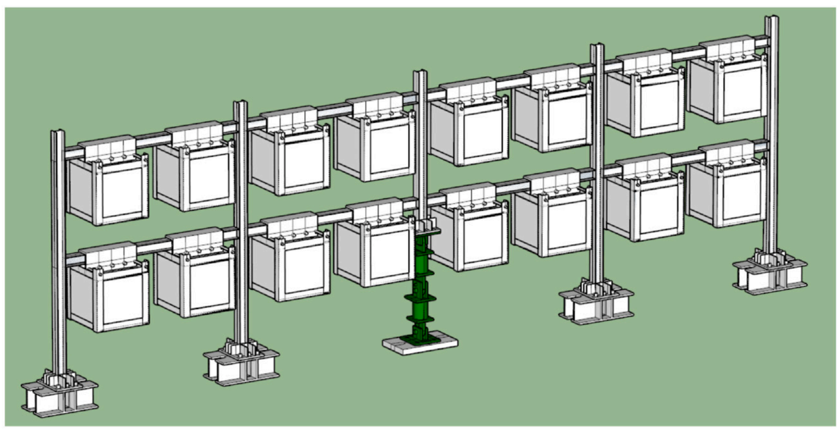


Fig. 7. Schematic diagram of test steel frame, as reported in [32]. The dummy column is shown in green color. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

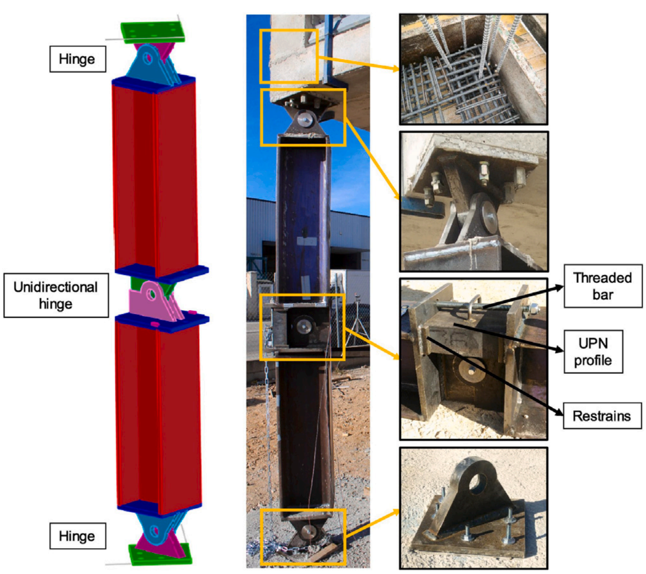


Fig. 8. Details of dummy column design and installation, as reported in [30].

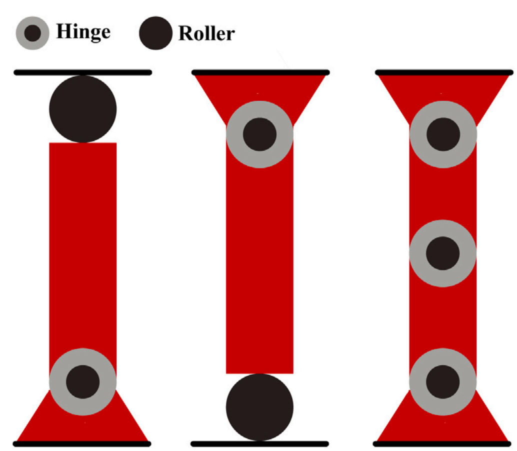


Fig. 9. Basic reported configurations for dummy column.

can be used in both steel and RC frames, a configuration of hinges and roller is usually adopted [19,26,30,33–35,53,54]. The most frequently reported configurations including three-hinged and pinned-roller are illustrated in Fig. 9. In the latter, i.e., pinned-roller configuration, the roller can be at the top or the bottom of the dummy column. The roller can be in the form of a single steel ball, or an assembly of ball bearings [37] to eliminate the friction as much as possible and facilitate the dynamic column removal. However, other innovative configurations, namely scissor arrangement [39,45], are also reported in the literature.

In the alternative approach, the structural column is weakened to allow releasing the axial loads under a specific mechanism. This weakening can be in the form of a partial cut of steel cross-section (see Fig. 10), cutting reinforcement bars in RC column, or even replacement of a specific length of the column with the weaker material, namely masonry. For example, in the studies reported in [55,56] exterior structural columns were first torched near the top and bottom. Only a small portion of the flange was left intact. Such measures facilitate fast and easy dynamic column removal. In other words, in this approach,

Fig. 10. Dynamic column removal in existing steel frame building; (a) torching of the removed column, (b) column ready to be pulled out, and (c) removal of the column, as reported in [56].

the structural column is converted into a dummy column either by weakening (in the existing structure) or building it weaker (in the lab). The weak part then undergoes (horizontal) loading in terms of pulling, pushing, impact and even blast to trigger the dynamic column loss. The triggering mechanisms are discussed in the next section.

Dummy columns, due to their geometry and configurations, usually allow limited vertical displacement, say a few dozens of centimeters. This limit is usually enough for the column removal tests. However, when large displacements are anticipated, or the development of full catenary action in the beams is of interest, some modifications in the configuration are needed. Next-generation collapsible column allows large displacements in order to activate catenary action in the beams. Fig. 11 shows the configuration and mechanism of such a novel collapsible dummy column.

2.2.2. Triggering mechanisms

Since different forms and configurations are used for dummy columns, the triggering mechanisms are also very different. The adopted triggering mechanism is also related to the constructional material, lab equipment and the size and shape of the specimens. Regardless of the adopted triggering mechanism, the underlying characteristic is the releasing of the axial force in a very short period of time to allow dynamic column removal. For example, in the experimental test reported in [33], the duration of the axial force release is 9–11 ms. However, the column removal time when the dummy column is used is not always well-documented.

Impact. When hinges and roller configurations are adopted, an impact can easily lead to the instability of the dummy column and therefore, dynamic column removal. A pendulum hammer usually serves this aim [26,34,41,43,59]. For example, as reported in [32], a removable column made up of a three-hinged strut kept in a straight position by inserting a brittle (glass) locking rod through an additional hole at the middle hinge is adopted. Then, the glass locking rod was broken by the impact of the pendulum hammer (see Fig. 12), and this triggered the hinge mechanism and eliminated the axial load-carrying capacity of the dummy column. A similar approach is adopted in the majority of the dummy columns that included hinge-roller configurations. A projectile fired by a compressed gas gun is also suggested for releasing the axial force in dummy columns [60–62]. In this technique, concrete blocks are usually inserted in the mid-section of the column to facilitate dynamic removal.

Based on the results reported in [47,63], when a dummy column and hammer are used, the column removal time can be less or more compared to 10% of respective vertical natural periods. Therefore, the maximum dynamic effect is not necessarily captured. However, even in a real incident, column loss is not always instantaneous [1,64]. Nonetheless, column removal time between 3–5 ms that perfectly satisfied the code's requirements is also reported [43]. The available information for column removal time is listed in Table 1.

Pulling and pushing. Similar to what was mentioned for the "impact" approach, the axial force in the dummy column can be released by pulling and pushing. Pulling and pushing forces are usually applied with different types of industrial trucks, either directly or by a device like rope and chain. This methodology is reported not only for hinge-roller configurations but also for weakened columns. An example of this method in an existing building is shown in Fig. 10 in which the middle segment between the torched sections (the weakened part) was pulled out by a bulldozer using a steel cable to simulate the dynamic column loss [55,56]. Another example of a pulling technique is reported in [48] in which a rope attached to the bar was pulled sharply to unstabilize a roller-based dummy column. A similar methodology is also illustrated in [37,54,65]. The ball bearings system, compared to a single ball roller, provides a low-friction interface resulting in a maximum required pulling force of less than 500 N, as presented in [37]. The pushing approach is also reported in the available literature [30]. The methodology is very similar to what was explained for the impact approach, but the applied forces are smaller and in some cases a touch is enough to release the mechanism. Fig. 13 shows an example of these techniques that can be compared to Fig. 12.

Pneumatic devices. Two basic concepts for dummy column are discussed earlier in this section; i.e., pin-roller configurations and weakening strategy. While the impact and pulling/pushing approach is mainly reported for the former, pneumatic devices (air gun, gas cannon, etc.) are also suggested for the latter. A scissor jack and a steel tension cable with a pneumatic quick-release mechanism are suggested in [39,45].

An interesting example of such a technique in which the dummy column is actually merged with the pneumatic device is shown in Fig. 14. The system includes an air compressor (supplying compressed air to the cylinder), a pressure gauge (displaying the air pressure), a solenoid valve (controlling the air direction to intake and exhaust), a switch (controlling the solenoid valve), and air pipes [66].

2.3. Explosion

Using explosives for column removal is discussed in this section. It should be noted that the discussion here is limited to a very narrow field in which explosion is used as a column removal technique. Therefore, blast-induced progressive collapse and demolition techniques are outside the scope herein. In the scope of the present discussion, the explosion effects are limited to a single column and the main purpose of such measure is to remove the selected column suddenly and completely without any loading (over-pressure or fragmentation) to other structural members. To guarantee such a requirement, special measures should be taken. Therefore, while lessons can be learned from building demolition and blast-induced progressive collapse, a very special application of explosion is considered herein.

Explosion techniques, for obvious security reasons, have been very rarely used in lab tests, especially because complete column removal needs considerable energy, and consequently, large explosive charge weight. Such large weight can lead to strong blast waves and high-speed fragmentation that is not safe for indoor applications. However, for existing and build-on-purpose structures in open areas, explosion techniques can provide fast and easy solutions. The explosion techniques were mainly used in reinforced concrete frames. The application of such a technique in steel structures is not well-documented. The limitations and possible improvements are discussed herein. The categorization of the material into "existing structures" and "built-on-purpose structures" is only for convenient discussion. They are basically similar referring to the column removal method, as already pointed out in Section 2.

The intensity of an explosion basically depends on two parameters, charge weight and standoff distance. Since in this technique the explosive is actually installed inside the column (or at least in contact with the column), charge weight is mainly responsible for the outcome.

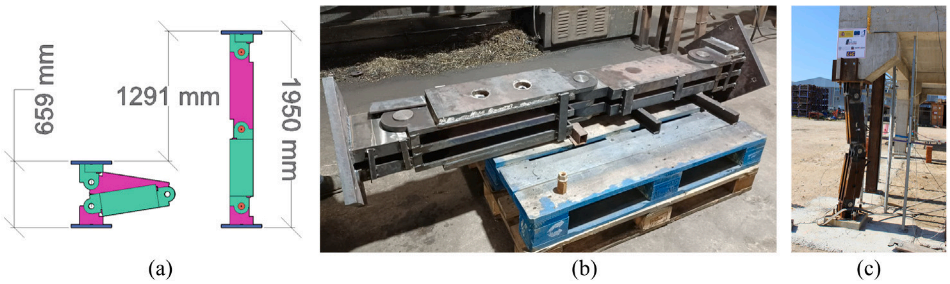
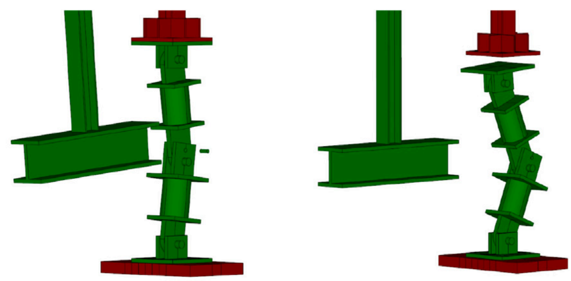


Fig. 11. Next generation collapsible column; (a) schematic view, (b) overall configuration and (c) installation in structural assembly. Test performed at Universitat Politècnica de València [57,58].



a. Breaking of the glass rod b. Activation of the hinged mechanism

Fig. 12. Schematic of dynamic column removal process with a pendulum hammer, as reported in [32].

Fig. 13. Dynamic column removal in dummy column assemblies (a) pushing by slight destabilization of the column using a forklift, as reported in [30] and (b) pulling, the cables were connected to a hydraulic jack (test performed at Universitat Politècnica de València [57]).

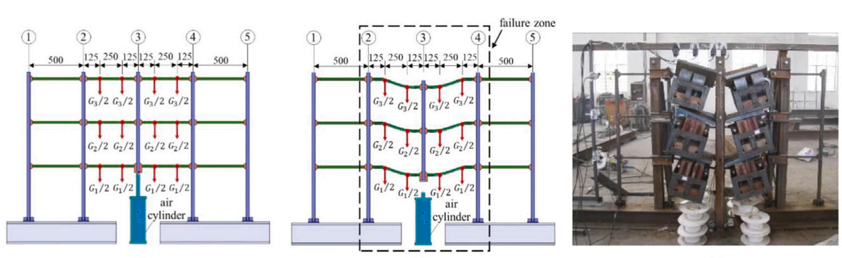
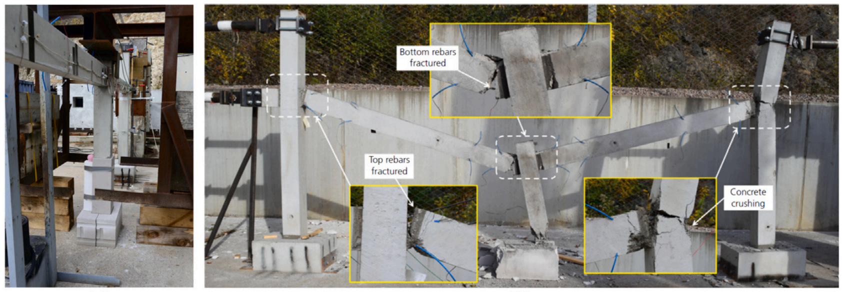


Fig. 14. Dynamic column removal process with a pneumatic device; (a) schematic view of the initial condition, (b) schematic view after column removal and (c) specimen's deformed shape after the experiment, as reported in [66].

However, the available literature does not provide enough details on charge weight, type and shape (for example, 120 g of C4 explosive is reported in [67]). Therefore, the explosive charge weight should be very deliberately selected. A strong explosion can destroy the column suddenly and completely, which is favorable, but at the same time it also leads to overload and fragmentation of other members, which is unfavorable. The energy produced by such a explosion is mainly dissipated by the fragmentation. On the other hand, if the explosive is not strong enough, complete and sudden column loss will not happen.

Considering the expensive and time-consuming nature of such tests, it is recommended that a pre-test on a single column and/or numerical simulations should be performed to decide the best size, shape and location for the explosive charge that can lead to sudden and complete column loss with negligible effects on other parts of the system [4]. Computational simulations can also be adopted for checking the reliability of the results. After an explosion, waves propagate in all directions. Therefore, some parts of the column will suffer upwards movement due to the explosion. While based on some literature the



(a) (b)

Fig. 15. Blast-induced column failure in a RC substructure; (a) general assembly and the location of the explosive charge and (b) failure and damage pattern after the test, as reported in [73].

blast waves have a low impact and do not influence the vertical movement of the structure [28], the impact of this phenomenon on dynamic column removal response should also be scrutinized. If the estimated explosive charge weight is too large for safe and accurate application, some weakening measures may be applied to the structural column, so the dynamic column removal can be performed by a lower charge and consequently a safer circumstance.

2.3.1. Existing structures

Explosives as dynamic column removal technique is originally suggested and implemented by Sasani et al. [68–71]. In this methodology, explosives were inserted into drilled holes in the column. The columns and beam portions were then well wrapped with a few layers of protective materials before the explosions were set off to avoid flying debris and fragmentation after explosion [70].

Similar approaches to Sasani's methodology are also adopted by other researchers [28,67]. Some other special measures occasionally are taken prior to the test. For example, cementitious grout was applied to the jagged surfaces of the first-floor columns and second-floor beams originally cast against masonry. This grouting was done to help prevent large chunks from dislodging during the test and make identification of cracking from test deformations easier [67]. Sometimes, the column is weakened before the explosion to facilitate the complete sudden column loss. In this case, the entire methodology is similar to the dummy column concept in which an explosion just acts as a triggering mechanism. For example, in the test reported in [67] partial depth saw cuts were sliced into a selected column at various elevations in the explosive zone to cut the longitudinal column reinforcement bars and ensure this bar would not remain continuous after the explosion.

2.3.2. Built-on-purpose structures

Progressive collapse tests on built-on-purpose multi-story structures are really rare. But, at the same time, such studies are among the most important research that can provide a deep understanding of real structural response in progressive collapse scenarios. Compared to the tests on existing structures, the results obtained from built-on-purpose models are more accurate, since they are extracted from deliberately constructed models with very clear material and geometrical properties. The approach is very similar to what has been already discussed for existing structures. Obviously, there is no need for drilling holes in the column, since explosive can be installed in the construction phase [72]. Contact detonation [27,73] as an alternative to the installation of the explosive inside the column is also reported for substructure RC specimens. While the majority of progressive collapse tests using explosion are devoted to the multi-story frames, few studies have focused on subassemblages [27,73]. Fig. 15 illustrates an example of blast-induced column removal in a RC substructure. In such studies, the differences between different experimental progressive collapse techniques are clearly highlighted [73].

3. Discussion

Based on the progressive collapse codes and guidelines, the dynamic column removal should be sudden, complete and without any overload and damage to other members. While these requirements are perfectly met in the current numerical methodology [74], for experimental tests more research is still required. In this paper, the most common experimental dynamic column removal methods are reviewed. While the dynamic method is a key step toward a more realistic progressive collapse assessment, several improvements are still needed to enhance the current methodology.

The majority of adopted methods, except for the explosion (see Section 2.3) are not accounted for moment transfer. Both dummy column and quick-release devices solely consider the axial action. This limitation may lead to different levels of inaccuracy based on system topology and location of initial damage. For example, if a frame system is very irregular (in structural topology, loading scheme, or boundary conditions), the influence of the acting moment cannot be ignored. Moreover, in some special cases, namely underground structures, the columns may undergo non-negligible shear forces. Therefore, in such cases, neither the dummy column concept nor quick-release devices can be used without losing the real structural behavior. As a very matter-of-fact, except for the explosion approach, other methods, i.e., dummy column and quick-release devices, are unable to consider the real initial conditions. Engineering judgment and/or pre-analysis are needed to determine the exact impact of such simplifications. If necessary to consider the perfect initial condition, novel techniques based on electromagnetic failure excitation devices can potentially be considered [75].

Another important issue, that is almost completely neglected in the current methodology, is related to the column removal time. Based on several published studies, column removal time has a major influence on the structural response [8,64]. However, in the current experimental literature, column removal time is not easily adjustable. Referring to the column removal time three characteristics are of particular interest; (i) measurability, (ii) repeatability and (iii) adjustability. Measurability is important to extract the exact column removal time that is necessary for verification and validation of the developed finite element model based on the experimental study and also for comparison of different column removal cases. The cases are comparable only if the column removal time is equal (or be short enough to capture full dynamic effects) for all cases. Repeatability is a key feature so it can be checked if the column removal time is equal for all test cases in an experimental program, especially when other parameters are changing. Adjustability is important to check different column removal times, since, in real scenarios, the damage is not always instantaneous. Therefore, if the test program focuses on a specific threat, in a scenario-based or parametric approach, it is necessary to change the column removal time based on the requirements of the program.

As reviewed, the body of the literature can be categorized into the three reported groups. However, it should be noticed that new

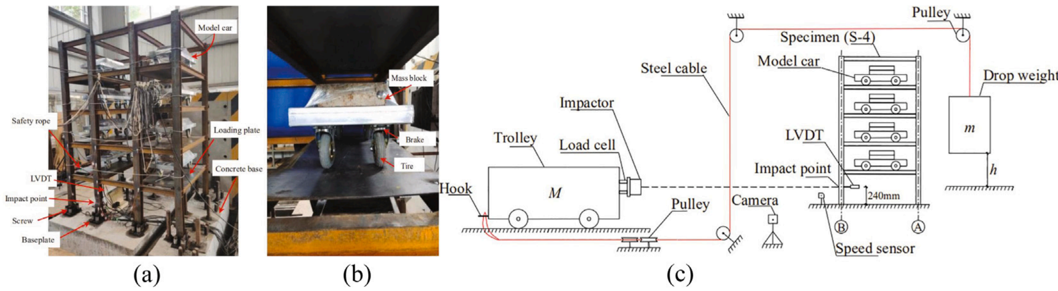


Fig. 16. Experimental tests on steel frame structure subjected to vehicular collision; (a) steel frame model structure, (b) vehicle model and (c) schematic view of horizontal collision facility, as reported in [80].

concepts can be fueled by the ideas already used in threat-dependent experimental progressive collapse studies. Full-scale threat-dependent tests of building structures subjected to extreme loading conditions are truly sparse [76]. While limited in number, the concepts that are used in [77–80] for impact-induced progressive collapse and in [81,82] for fire-induced progressive collapse can be potentially considered for dynamic column removal tests. It should be noted that threat-dependent tests are usually performed on the intact model. That means the target column is in a perfect state regarding strength and boundary conditions. Therefore, unlike the current mainstream, the perfect initial condition can be guaranteed, that obviously is of great importance for dynamic tests. Fig. 16 illustrates an example in which the structural response of a steel garage subjected to vehicular collision is experimentally investigated.

While not explicitly documented, the safety of operators is one of the major issues that should be considered in any progressive collapse tests. Some dynamic column removal techniques, namely the dummy column approach, are inherently safer than others, say explosion techniques. Special care should be given to the collapse tests on existing buildings since different uncertainties are always involved in such situations that can lead to safety issues for the operators.

4. Conclusion and future directions

Experimental tests, usually, act as a basis for verification and validation of the numerical simulations and for improving and updating the current guidelines and codes. But, for dynamic column removal tests, a rational framework for assessing the accuracy of the experimental approach is first needed. In this regard, the situation of the targeted structure, that the experimental setup aimed to represent, should be carefully checked. Namely, special emphasis should be put on the irregularities in loading and configuration. Only with such considerations, simplifications that are usually applied to the initial conditions can be justified; either if it is a rational simplification, or not. In the latter case, some currently adopted techniques cannot be used. With a downpour of recent studies on experimental dynamic column removal, there is a growing need to re-visit and review the existing research methods to update both research and practice methodology. Obviously, there is also room for further studies on developing novel techniques, too. In the following, the main challenges and foremost future prospects are abridged.

- In a real collapse scenario under a specific threat, the occurrence of "complete" and "sudden" column loss is a rare event, instead, a specific level of damage is usually materialized in a certain period of time [83]. In other words, sudden and complete column removal is a conservative simplification of the real phenomenon, and it can be observed only in special circumstances, i.e., small near-field blasts or high-speed impacts. The development of more general experimental configurations for the modeling of different levels of damage in the column enables the opportunity to perform more realistic progressive collapse tests.
- In the current dynamic column removal techniques, column removal time is neither easily reproducible nor adjustable. This shortage leads to two problem classes; first, column removal time cannot easily and directly adjust to serve the research needs, and second, there is no guarantee that column removal time is equal for different cases and scenarios in the experimental program. This issue should be addressed in future studies.
- The adopted column removal techniques should satisfy the initial conditions of the intact model. In the current experimental methodology, except for some cases in the explosion approach, initial conditions cannot be perfectly guaranteed; the focus is usually put only on the axial force of the column and not all the acting components. The consequences of such a simplification are dramatically related to the model configurations, namely the possible irregularities, column removal location, etc. Anyway, such simplification cannot be recommended as a general role, and a special focus on the development of a more effective methodology is necessary.
- In the absolute majority of the current literature on experimental techniques for dynamic progressive collapse tests, initial failure occurs in the column. However, initial failures can also be observed in the beam, bracing and wall, usually accompanied by column damage/failure. This issue is partially addressed in the current numerical literature [4], but there is no methodology to consider such a removal/damage to the lateral load-bearing members in the experimental studies. Therefore, more research emphasis to overcome this shortage is needed. Developing the techniques for removing the structural members, in a more general way, can provide more opportunities for experimental studies. Such techniques can also be used in non-building structures, namely space structures. While not directly in the scope of the current survey, special scenarios, like punching shear failure, need more attention, a technique to model the dynamic shear failure can be the first step for controlled pancake-type progressive collapse tests.
- Multiple-column loss, either due to a large threat or repeated threats, is observed in several real incidents. However, the current literature on experimental progressive collapse studies has mainly focused on single-column removal scenarios. In this regard, modification of the current methodology or development of new techniques to address this need is required. The new approach for simultaneous column removal may consist of using cables connected to different joints. After releasing the cables, multiple-column removal would occur. However, the new technology should address the column removal time and the sequence between removal scenarios, as well as initial conditions, since the impact of such issues is much more important in a large initial failure regime or consecutive local failures.
- The absolute majority of the available experimental literature is devoted to column removal at ground level, especially in a single or two-story substructure. Column removal in the upper story has its special requirements and the current techniques cannot be

directly used for it. In this regard, developing new techniques for efficient column removal regardless of the location of the column in the structural system is important and should be addressed in future research. For such a technique, safety concerns should also be considered.

- There has been a surge in research focusing on the impact of infill walls on the progressive collapse response. While numerous numerical studies have been conducted to investigate the performance of frames with infill walls subjected to sudden column removal, there is a lack of documented experimental studies in this area. It is important to note that the inclusion of infill walls and other secondary collapse-resisting mechanisms in the setup can influence the usability and performance of column removal devices. Therefore, there is a need for further research to address the dynamic column removal in infill frames.
- Progressive collapse tests are inherently costly and time-consuming. Therefore, the re-usability of the developed column removal devices is of great interest. While such measures are partially reported in the literature [30], much more emphasis is still needed.
- Structures under construction and temporary structures are very prone to progressive collapse and several real progressive collapse incidents occurred in such systems [84,85]. Experimental dynamic failure of formworks, falseworks, shuttering and especially scaffolding is very rarely studied. More research focus is needed to shed light on the dynamic failure of temporary structures, as well as to develop lab equipment to test such phenomena.
- There is very rich and well-developed literature on demolition techniques. When a mechanical approach is chosen, tools ranging from wire saw to wrecking ball to remote control truck and hydro-demolition are documented. Alternatively, demolition can be done by using chemical techniques including but not limited to explosion and bursting. While there are inherent similarities, there are not enough conversations between demolition and progressive collapse field in general, and dynamic column removal in particular. Obviously, such techniques cannot be used directly for dynamic column removal, but demolition techniques can serve as an idea pool for experimental progressive collapse studies.
- Progressive collapse of the non-building structures, namely space structures, is attracting more and more researchers. However, few studies are devoted to dynamic experimental tests. An interesting member-breaking device including springs and electromagnets is reported in [36] for member removal in planer trusses. Such concepts can be used for dynamic member removal in space structures too. Moreover, while some famous collapse incidents are reported for steel truss bridges, not enough experimental dynamic tests are documented on such structural configurations. In this regard, more emphasis on member removal techniques in non-building structures is necessary.
- Safety during the tests is one of the major issues in dynamic progressive collapse tests that has not been well-documented so far. Some solutions are unsafe for the workers, while others are much more reliable and safe. Safety concerns should be clearly mentioned when reporting a test, and the measures to guarantee the workers' safety should be suggested and discussed in detail. Moreover, in developing new techniques for column removal, or modification of the existing ones, safety issues should always be scrutinized and clearly reported.
- New techniques that are already used in threat-dependent progressive studies, as well as approaches used in other industrial fields can be scrutinized to develop novel and more efficient dynamic column removal techniques. Especial emphasis should be put on the electromagnetic and mechatronic devices since such an approach is very rarely reported in the current experimental progressive collapse studies.

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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