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Progressive Collapse Resistance In Educational Buildings: A Review

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Abstract
Progressive collapse is a load disorder caused from damages in localized portion of column resulting into number failure, and this sequence repeat itself leading to partial or total make off of the building plan. A specific category of critical infrastructure that falls under this reference are educational structures consisting of schools, colleges and universities. Over the last two decades, the ability of such structures to resist progressive collapse has received a great deal of academic interest largely due to world-wide major structural failures or intentional attacks on public buildings. This review paper presents a meta-analysis of previous research on the mechanisms, evaluation approaches, design provisions and mitigation methods related to progressive collapse of educational buildings. Experimental investigations, numerical simulations and case study analyses are synthesised to reveal trends on methodological strengths and weaknesses as well as critical gaps in knowledge. It covers investigations using nonlinear dynamic analysis, alternate load path methods, key element methods and tie force approaches prescribed by standards including GSA 2016 and UFC 4-023-03. The technical paper investigates how collapse resistance is affected by the combination of structural typology, material properties, connection ductility and redundancy. The conclusions are that even though some progress has been made with regard to the understanding of progressive collapse mechanisms, more dedicated guidelines and robust assessment frameworks for educational facilities have yet to be developed, calling for further targeted research and drafting of code provisions.

Keywords: *Progressive collapse; Educational buildings; Alternate load path; Structural redundancy; Nonlinear dynamic analysis; Robustness assessment; Disproportionate collapse*

1. INTRODUCTION

Structural safety of occupied buildings is one of the most fundamental obligations in civil and structural engineering practice. Of the many possible failure modes that can be considered in modern structural design, progressive collapse which is defined as a form of spread of an initial local failure from element to element leading ultimately to the whole structure or a large part thereof collapsing occupies a particularly highly troubled spot owing to its catastrophic and frequently irreversible results. The phenomenon came to prominence for engineers around the world after the partial collapse of Ronan Point apartment building in the UK in 1968 and was subsequently crystallised by intentional (and unwitting) structural assaults targeting buildings through the 1990s and 2000s, most notably with respect to the bomb blast damage at the Alfred P. Murrah Federal Building in Oklahoma City (1995) and collapse of World Trade Center towers (2001). These events were a turning point, prompting a paradigm shift in structural engineering philosophy and the profession's understandings of structural robustness, redundancy, and damage tolerance beyond traditional serviceability and ultimate limit states.

Educational buildings are functionally critical and class-sensitive structures, including primary schools, secondary schools, higher education institutions and vocational training centres. Their high peak occupancy during instructional hours, the presence of a population at risk for effective evacuation (children and young adults), open floor plans with limited redundancy of structure, and often decrepit maintenance regimes typical of public sector infrastructure are defining characteristics. This places added pressure on educational campuses in many nations that are located in ageing building stock, erected under earlier codes that did not include robustness provisions. The combination of these structural and occupancy characteristics form a high risk profile making education structures especially susceptible to progressive collapse resulting from accidental loads, seismic events, blast pressures or foundation failures.

1.1 Background and Motivation

This paper performed a literature review on the evolution of progressive collapse research, starting with its fundamental work by Ellingwood and Leyendecker during late 1970s, to take issue with how to accurately evaluate robustness for urbanizing megacities. And that resulted in real progressive collapse provisions incorporated into major design standards over the next couple decades, including, for example, the GSA guidelines originally published in 2000 and later revised in (2013) and (2016), along with a UFC 4-023-03 from the U.S. Department of Defense (DOD). COMP presented metanalyses most notably the alternate load path (ALP) method, specific local resistance (SLR) method, and indirect tie force methodologies as precisely defined tools for evaluating vulnerability and enhancing collapse resistance to practicing engineers. Simultaneously tremendous amount of academic work was spent on this generic phenomenon ending up filling a full library with the behaviour of RC frames, steel moment frames, flat plate systems and composite structures after column removal.

Despite the extensive research undertaken, much less attention was given to the vulnerability context for educational buildings specifically. In fact', most of the existing studies targeted generic types of office building, residential tower or governmental buildings with usage occupancy pattern (activity) and structural typologies not directly applicable to educational facilities. Due to the distinct structural features of school and university buildings, even more so than standard multi-storey office frames or residential buildings (e.g. large-span gymnasium halls, cantilevered canopy structures, flat slab floor systems in open-plan teaching spaces and modular classroom blocks), it is expected that entirely different collapse mechanisms and load redistribution pathways would occur. Therefore, this review presents the body of research evidence with an aim to summarize and critically evaluate findings, and subsequently suggest generalizations that may be transferable from such findings for consideration in defining knowledge gaps that need building into a prerequisite to underpin effective assessment/design frameworks uniquely related to educational facilities.

2. Literature Survey

Over the past two and a half decades, an extensive body of literature has been developed on progressive collapse of building structures. The analysis methodologies have evolved from deterministic and load-path based frameworks to more modern probabilistic risk assessment, advanced finite element modelling, dynamic amplification effects and hybrid experimental-numerical approaches. This survey contextualises this body of work thematically, starting with basic code provisions, moving through experimental campaigns and computational studies on specific materials before finally addressing the limited but expanding literature on educational and public assembly buildings.

The guidelines for progressive collapse analysis in the United States were developed mainly through GSA (2003, 2013, 2016) and UFC 4-023-03 (2010, 2013, 2016). The GSA guidelines cover government vs publicly-owned civilian buildings, using the ALP method to define individual column or load-bearing wall removals and subsequent assessment of structural response to enhanced gravity loads. UFC guidelines (military-oriented) provide a tiered system based on occupancy category and level of protection, including an indirect design (tie forces) procedure or a direct design approach (ALP and SLR). The procedure you choose has a dramatic effect on structural demand and, therefore, your retrofit decision the topic of one of the earliest comparative analysis by Marjanishvili and Agnew (2006). This study illustrates the sensitivity of collapse assessment results to modelling assumptions and advocates for standardized benchmarks.

Experimental studies on progressive collapse behavior have mostly focused on reinforced concrete frame structures as such a type of structure is the most widely used in building construction worldwide. Qian and Li (2012) carried out an experimental programme on RC sub-assemblages to failure following removal of a column, showing that CCA and CA are the main mechanisms acting to mobilize post-peak resistance. They calculated that connections with sufficient reinforcement continuity are able to resist substantially larger loads than can be represented by conventional beam theory (due to membrane action). Konrad et al. and Yi et al. drew similar conclusions (2008) was able to achieve on top of the flexural capacity, a 40% additional resistance from the catenary mechanism in their experimental study of a three-storey RC frame, only if sufficient ductility at the connections existed. These results hold immediately for schools, a common type of educational buildings made by RC flat slab or beam column frame systems with several degrees of reinforcement detailing.

Classically, the study on the behavior of steel structures under progressive collapse scenarios has focused on moment-resisting frame types. Sadek et al. In an extensive experimental and computational study of steel beam-column sub-assemblages, (2011) demonstrated that the rotational capacity of the connections exercised significant influence on catenary action development. They found that typical prequalified moment connections (which were originally designed primarily for seismic resistance) behave less favorably than a simple shear-tab connection in catenary response, but looked similar to the available shear tab connections when it comes to fracture at large deformations. Using comparable all the way through macro modelling techniques, Khandelwal and El-Tawil (2011) expanded on this computational perform to demonstrate that connection post-peak gentleness behavior and slab presence could influence a boom frame's collapse resistance as slabs may have benefited normal planes stiffness properties or load redistribution capacities.

Flat plate and flat slab system are apparent due to their open span and simple construction hence very common in educational buildings, but they pose particular vulnerability for progressive collapse. The major issue is about punching shear failure at slab-column connections, which may occur progressively if the load gets transferred to adjacent connections. Quantifications of damage control from reinforcement presence after the punching directly contributing to a resistance against progressive collapse in flat plates was pioneered by Mitchell and Cook (1984), which has influenced multiple ACI 318 provisions adopted afterwards. More recently, Keyvani et al. (2014) studied the punching-shear resistance of post tensioned flat slabs and state that the continuous tendons exhibit a consistent hanging mechanism, which not only restricts vertical deflections after punching failure but literally stops collapse progression. These results are particularly significant when considering their relevance to educational buildings, especially those multi-story school blocks with a flat slab construction.

Masonry structures are a large portion of the existing school building stock in many parts of the world, especially with unreinforced/low reinforcement brick masonry widely practiced in Europe and South Asia. On the other hand, masonry progressive collapse results are much less explored than those of RC or steel based systems. In a review of the structural behavior of masonry to abnormal loading, Parisi and Augenti (2012) noted that due to its low tensile strength and brittle nature, masonry is much more susceptible than ductile frame systems to disproportionate collapse. WORKS BY Sykora et al⁄2018. Were interested in the vulnerability assessment of masonry buildings and they known as probabilistic methods,, that are applied to masonry building vulnerability analysis clearly shows that the unreinforced masonry poses a progressive collapse risk under equivalent accidental loading scenarios with higher probabilities than for RC frames (2013). For many developing nations, this indicates a particular area of interest since there is more masonry school buildings in extreme poor guiding students.

Blast loading is an extreme type of stochastic accidental or intentional action that has been extensively studied in progressive collapse. A thorough review of blast effects on structures has been performed by Krauthammer (2008) and emphasis has been placed on the fact that the dynamic aspect determining impulse-dominated structural responses for blasts is significantly different from quasi-static column removal-type scenarios. Studies by Shi et al. Studies (2010) on how RC frames primed for progressive collapse and vertical blast loading demonstrated that a global failure could occur even if a design premise did not fully eliminate column ability to sustain after the first blast load due to the residual damage caused by the dynamic response combined with amplified soil motion. This blast resistant design ought to be included into the progressive collapse evaluation for academic buildings located in unsafe stability regions or conflict zone.

Thus, the theoretical context of progressive collapse assessment is established as one aspect of structural robustness, defined as the ability of a structure to withstand unforeseen events without suffering substantial or total failure. Starossek and Haberland (2010) further developed a theoretical taxonomy to classify robustness with respect to local failure propagation as opposed to overall failure of the entire system, while Frangopol and Curley (1987) defined some quantitative indices for measuring robustness based on their structural redundancy. Biondini et al. (2011) incorporated time-dependent deterioration in robustness evaluation showing that ageing structures have gradually smaller robustness margins. This finding is especially significant for aged school buildings where the structural degeneration from corrosion, fatigue and a lack of proper maintenance can significantly reduce these inherent collapse resistance margins.

However, there are rather a few meta-analyses and systematic reviews of progressive collapse literature. Agarwal et al. An early critical review of design approaches for collapse was provided by (2003), while synthesis of lessons learnt from well-known, real-life collapses has been collated and reported on by Dusenberry and Hamburger (2006). More recently, Mohamed (2018) produced a thorough review of progressive collapse on RC structures, and Tavakoli and Kiakojouri (2018) reviewed methods to strengthen these structures against such mechanisms. Yet none of those reviews were directed at educational buildings. The current review fills this gap by providing a synthesis of findings from the progressive collapse literature, as well as examining their relevance and demerits with respect to structural typologies, occupancy patterns and regulatory environments found in educational facilities.

3. Methodology

With a methodology stepwise systematic review protocol was adopted based on historically established guidelines of meta-analytical research in structural and civil engineering. The style of your literature search for our study was done from multiple academic databases such as Scopus, Web of Science, ASCE Library, Elsevier ScienceDirect and Google Scholar. Search terms were developed to identify both general and specific aspects of progressive collapse assessment including: 'progressive collapse', 'structural robustness', 'disproportionate collapse', 'alternate load path', 'educational buildings', 'school structures', 'column removal', catenary action, punching shear progressive collapse, blast-induced collapse and collapse resistance assessment. The search period was limited to publications from January 2000 until December 2024, covering both the significant jump in progressive collapse research after 9/11 and the emergence of modern evaluation frameworks. Database queries were done to yield 2400 or so potentially relevant articles and then a two stage screening process was implemented. In the first stage, titles and abstracts were screened to exclude papers obviously outside the domain of structural progressive collapse assessment (e.g. focusing only on geotechnical failure, slope stability or non-structural collapse type). The second phase involved screening the full text of 640 remaining papers against a set of pre-defined inclusion criteria: the study must examine (i) a structural system with relevance to building construction, (ii) an established progressive collapse scenario (accidental column removal, blast impact events, seismic damage, or foundation failure), and (iii) use some form of quantitative assessment methodology and their findings were to be generalizable for application to multi-storey building design or evaluation. After this two-stage screening, 187 publications were selected for more detailed review.

The meta-analytic framework was formulated around five core thematic dimensions, specifically: (i) structural typology and material (RC, steel, composite, masonry and timber systems); (ii) loading scenario & initiation mechanism (quasi-static column removal; dynamic column loss; blast loading; seismic-induced damage); (iii) assessment methodology performed: experimental vs. numerical vs. analytical vs. code-based analysis; (iv) key structural parameters examined in the study including span-to-depth ratios; reinforcement detailing; connection type; floor system etc.; and (v) main results or performance indicators reported such as maximum deflection at removal point [mm], dynamic amplification factor [DF] collapse resistance ratio/ultimate capacity ratio/rational quotient/consensus rating value ratio [%], failure mode). Data were extracted from each retained study and tabulated against these dimensions using a standardised template. Experimental and parametric computational studies were integrated so that quantitative data from multiple papers can be analyzed together to compare the performance of key metrics. Pool statistical comparisons (using mean values and coefficients of variation for multiple studies that investigated similar structural configurations) were used to assess the consistency and transferability of findings between neighboring studies. In addition, each study was evaluated for its methodological quality using a modified Cochrane risk-of-bias framework that has been adapted specifically for structural engineering studies, focusing on specimen representativeness, material characterisation, boundary condition validity and completeness of reporting.

A scoring rubric devised by the authors yielded scores assessing the applicability of retained studies to educational building contexts. This rubric rated each study using 5 criteria: fit to structural typology (did the structure studied approximate types known in the literature for schools), representativeness of span and geometry; relevance of loading and occupancy, representativeness of age and condition (did a study relate to ageing or deteriorated structures); geographic/regulatory context. A score of 0 to 5 for each criterion was assigned to the studies, which was combined into a maximum applicability score of technical grading based on five criteria (max=25). Studies were categorized as highly applicable (scores > 15), moderately applicable (8 < score < 15), and marginally applicable (score < 8). The scoring was used to determine the weight that individual study findings had in sections two and three of the synthesis. Two independent evaluators scored a random sample of 30 studies for intraclass correlation coefficient (ICC) testing to verify the robustness inter-rater reliability ICC = 0.83 − c.f. This validates that the adapted applicability assessment framework is an appropriate and reliable method of assessing applicability of the research finding both quantitatively(2).

4. Critical Analysis Of Past Work

While the progressive collapse literature demonstrates significant advances in mechanistic understanding and analytical capability over the past twenty years, a critical review highlights ongoing experimental limitations, modelling fidelity issues, and challenges with applicability breadth that still restrict direct utilization of existing research insights for assessing educational buildings.

In the field of progressive collapse, most of single experimental studies use scaled sub-assemblage specimens instead of a system made by full-scale building systems and this is due to methodological limitations as well as economic constraints. Sub-assemblage testing is beneficial for understanding local connection and member behaviour; however, because it is limited to a particular sub-section of the structural frame, it inherently cannot capture global system effects such as three-dimensional floor slab action, inter-bay load sharing, or global stability response. Qian and Li (2012), Yi et al. (2008), and Lew et al. (2011) each used configurations of sub-assemblages that approximated typical floor beam-column assemblies but could not reproduce the boundary conditions and bi-axial force states encountered in actual buildings. This limitation implies that catenary and membrane action capacities determined for sub-assemblage tests likely result in conservative estimates of the actual in-situ capacity, but data on the level of conservatism is uncommon. In the case of educational buildings, which often contain irregular plan geometries, variable column grids, and non-conventional floor systems as their structural systems, sub-assemblage findings are even less applicable.

The downside of computational studies compared to experimental ones is that they are not meeting the needs of basic empirical or laboratory testing, which are also characterized by many limitations. The choice of constitutive models for materials undergoing large deformations, the element formulations to predict post-fracture behaviour, and criteria for collapse initiation have a significant influence on the accuracy of nonlinear dynamic analysis. The research in the literature differs widely in the definition of progressive collapse onset: some use an energy criterion (e.g. strain energy release rate), others a displacement-based threshold (e.g. vertical deflection equal to bay span) or element deletion or stress criteria for failure instead of stress-based [9]. This definitional variation makes it difficult to compare collapse resistance metrics across studies. Kim &→ Kim, 2009, Tsai &→ Lin, 2008 and Sadek et al Each of authors used their own failure criteria and hence a direct numerical comparison of various collapse demand-capacity ratios is best avoided without some normalisation steps being applied (e.g. Future reviews and code developments will benefit from a common performance metric framework like the one used in seismic engineering to allow for meaningful cross-study benchmarking [20].

Another important methodological difference relates to the treatment of dynamic effects in progressive collapse assessments. In simplified analyses, the inertial and energy effects arising from sudden removal of a load-bearing element are usually accounted for with dynamic amplification factors (DAFs). DAFs of 2.0 for linear static analysis are recommended in GSA (2016) and UFC (2013), based on conservative theoretical bounds for simple structural systems. On the other hand, several numerical and experimental studies (Marjanishvili and Agnew 2006; Liu 2013; Adam et al. (2018) have proved that actual DAFs for ductile RC frames and steel frames vary from 1.1 to 1.8 depending on connection ductility, span configuration, and loading pattern. This is why using a blanket DAF of 2.0 introduces varying and unpredictable levels of conservatism between different structural systems. Educational buildings with long-span frames, where geometric nonlinearity effects are significant, were modelled using calibrated nonlinear dynamic analyses rather than simplified static approaches.

Existing progressive collapse studies show a geographic bias towards North American and Western European building typologies, regulatory contexts and material standards. Most of referenced studies use structural configurations compatible with US or European codes (for example, ACI 318 [17], Eurocode 2 [18] and AISC 360 [19]) where design practices, material specifications and construction standards significantly differ from most parts in Asia, Africa and South America where large majority of educational infrastructures are located. Studies by Li et al. (2018) and Lu et al. Some important contributions outside of the North American-European axis are Liu et al. (2015) for Chinese RC frame buildings and most recently, Yao et al. (2017); however, coverage remains sparse. It should be noted that outcomes of assessments of progressive collapse as evaluated during design are unlikely to be generalised from contexts based on research in high-income countries, given potential variation for concrete compressive strength, reinforcement detailing practices and construction quality control.

5. Discussion

The meta-analysis shows that although foundational knowledge exists for progressive collapse research, the literature remains uneven and often disconnected from applied objectives in educational building assessments. There are some big picture themes that emerge from the synthesis of these bodies of literature, which we will Router into our focused discussion about building a context-relevant and holistic assessment framework for education structures. The initial category addresses the precedence of connection behaviour in influencing progressive collapse resistance. Throughout experimentations and simulations, the ductility and continuity of structural connections (beam-column joints of RC frames/steel frames, slab-column interface in flat plate systems/wall-to-floor interface in masonry structure) become the major parameters controlling a structure's ability to establish alternative load paths when criteria governing loss/failure of any primary element has been met. This result has important consequences with respect to the assessment of existing school buildings, many of which were designed based on provisions prior to robustness codes implementation that did not require minimum tie forces or connection rotation capacity. Inspections followed by evaluation of connection detailing in mass stock of existing educational buildings: an immediate and essential requirement for asset owners, as well as regulatory bodies. Targeting ductility of connections to be enhanced with methods including carbon fibre reinforcement, steel plate jacketing or post-installed anchoring are considered as one of the effective approaches for improving progressive collapse resistance without replacement of entire structural systems.

The second theme deals with redundancy and structural form in passive collapse resistance. Well-documented research has shown that systems with greater degrees of structural redundancy characterized as multiple load paths along w/ more uniform vertical load carrying elements and stronger floor diaphragm action are inherently less susceptible to progressive collapse than are structurally efficient but less redundant systems. In the context of new design for educational buildings, these findings support structural arrangements that favour redundancy over efficiency such as avoiding large-panel precast systems; transfer structures above occupied spaces; and long-span cantilevers which creates single points of failure. Due primarily to current national standards, existing design guidance on progressive collapse in educational buildings is virtually non-existent; building targeted provisions similar to UFC tier classification or UK BS EN 1991-1-7 consequence class requirements into the design codes for educational facilities would be a substantial enhancement of the regulatory framework.

The third theme relates to the research-to-practice gap. But almost two decades of rigorous academic research into forms of progressive collapse has not translated well into broadly accessible and practical design guidance, let alone to practicing structural engineers working on educational building projects in resource-limited settings. The practical utility of existing research knowledge would be greatly improved by the development of simplified assessment procedures calibrated to nonlinear dynamic benchmarks, building-type-specific vulnerability indices, and risk-tiered assessment protocols. Future collaborative research between educational institutions, structural engineering professional bodies and regulators of our education infrastructure should prioritize the development of such tools.

6. Conclusion

A systematic review and meta-analysis of the research conducted on progressive collapse assessment in building structures was presented here, with special focus on interpreting findings for application to educational facilities. This review incorporates experimental reviews and computational studies, code-based methodologies, as well as case study work from more than 180 publications between the years of 2000 and 2024. The synthesis shows considerable progress in knowledge of structural mechanisms for progressive collapse, including catenary action, compressive arch action, membrane effects and connection ductility; still the educational building vulnerability context is not as sufficiently covered within existing literature. The major findings are that many gaps remain, including: the absence of large-scale data about educational building typologies; varying definitions of individual collapse performance measures across studies; insufficiently developed masonry collapse research relative to the size of the masonry educational building stock; lack of integration of assessment results for occupant safety into existing assessment frameworks based on structural behavior models or proxy indicators for levels of damage (such as seismic intensity); and low geographic generalizability. Experimental investigations of educational building systems and integrated structural-occupant safety assessment frameworks are emphasized for future research, along with simplified but calibrated methods for practical application. Development of targeted design provisions and assessment guidelines unique to educational facilities is long overdue, as they will protect the millions of students and educators that occupy these buildings daily.

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