International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 04 Issue: 04 |Apr-2020 SJIF Rating: 6.049 ISSN: 2582-3930

Progressive Collapse Analysis

Chirag KaPatel
Assistant Professor, Department of Civil Engineering, DD University, Nadiad, Gujarat

Prajapati Mitesh
Student, L. D. College of Engineering, Ahmedabad, Gujarat

ABSTRACT

Progressive collapse, defined as the disproportionate failure of a structure triggered by local damage, has become a critical concern in the design of blast-resistant and high-risk facilities. Over the past three decades, major accidental and intentional events have highlighted the vulnerability of structural systems to localized failure and the importance of robustness, redundancy, and continuity in structural design. Among various approaches proposed for assessing collapse potential, the Alternate Load Path (ALP) method has emerged as the most widely accepted, codified, and implemented framework due to its threat-independent nature and compatibility with mainstream structural analysis tools. This paper presents a comprehensive state-of-the-art review of progressive collapse research with emphasis on the ALP method for blast-resistant design. Key contributions from international design codes, government guidelines, experimental investigations, and advanced numerical modeling are synthesized to trace the evolution of this methodology. Comparative evaluation with direct dynamic and energy-based approaches is provided to highlight strengths, limitations, and the role of ALP within modern design practice. The review also addresses emerging trends such as hybrid ALP-dynamic formulations, energy-based criteria, and probabilistic frameworks for risk-informed assessment. Finally, current gaps and future research needs are identified, including the need for expanded experimental databases, multi-hazard interaction studies, and codified performance-based design procedures. This review aims to serve as a consolidated reference for researchers and practitioners seeking to enhance the robustness of structures against blast-induced progressive collapse through systematic application and advancement of the Alternate Load Path method.

1. INTRODUCTION

The structural engineering field has seen a heightened interest in progressive collapse, particularly spurred by notable incidents like the 9/11 Attack. Over the last decade, a multitude of experimental studies have delved into the dynamics of reinforced concrete (RC) structures, shedding light on their resistance mechanisms, dynamic attributes, and the various factors influencing their response to progressive collapse scenarios.

In the realm of impact events, the peak force exerted endures for only a brief duration. A blast, characterized by a rapid chemical reaction, generates transient pressure waves known as shock waves. In the case of a ground-level blast device, the pressure wave emanates outward in a hemispherical pattern. The resulting shock wave loads directly impact the exposed surfaces of structures, subsequently transmitting these loads to other structural components. This contrasts sharply with ground motion, wherein the entire structural system experiences simultaneous inertial effects.

Structures engineered to withstand impact loads are subjected to a fundamentally different type of stress compared to those considered in conventional design practices. Here, structures face the rapid propagation of shock waves, capable of exerting pressures often significantly greater than those encountered even in the most severe storms.

Impact events can generally be classified as external or internal. An internal or confined blast yields shock loads or gas pressure loads resulting from the confinement of blast products. Explosives are categorized as either low or high explosives based on the amount of energy they release. An example of a low explosive is black powder, while common high explosives include RDX (Royal demolition explosive), Dinitrotoluene, TNT (trinitrotoluene), Pentrinite, Pyroxilene, Dynamite, Compound B, among others. The use of TNT typically serves as a reference point, with high explosives, apart from TNT, often expressed in terms of equivalent mass of TNT.

NEED FOR STUDY

Studying the dynamics and impacts of events like explosions is vital for various reasons. Firstly, it aids in designing resilient structures capable of withstanding such forces, enhancing public safety. Secondly, it contributes to establishing safety protocols, crucial for high-risk environments such as industrial sites and areas prone to disasters. Thirdly, it assists in assessing risks better, leading to improved management strategies. Additionally, research in this area drives innovation in construction materials and design techniques. Furthermore, it plays a crucial role in forensic analysis, providing insights into the nature and causes of explosions. Lastly, it is vital for national security efforts, aiding in detecting and preventing threats. Overall, studying impact dynamics is essential for advancing engineering knowledge and ensuring safety and security in various contexts.

2. Literature review

2.1 Historical motivation and evolution of practice

Progressive collapse — the disproportionate failure of a structure following local damage — rose to prominence after catastrophic events such as the 1995 Oklahoma City bombing and the 2001 World Trade Center attacks. Those failures emphasized that local element loss (e.g., a column) could precipitate widespread structural failure unless the global system provided alternative load paths or specific local resistance. The recognition of these events spurred the development of formal guidance and research programs focused on reducing disproportionate collapse risk and on understanding threat-dependent versus threat-independent assessment approaches.

2.2 Design codes and official guidance

Design guidance for progressive collapse has been promulgated by several agencies and standards bodies. The U.S. Department of Defense's Unified Facilities Criteria (UFC 4-023-03) and the U.S. General Services Administration (GSA) Alternate Path Analysis and Design Guidelines are among the most influential, establishing the Alternate Load Path (ALP) (also called Alternate Path Analysis) as the principal, threat-independent design approach for many new and renovated buildings. FEMA documents and NIST technical reports have further summarized methods for mitigating blast effects and introduced risk-informed perspectives. These documents codify (a) standard removal scenarios (e.g., single column removal at exterior/interior locations), (b) simplified load combinations for alternate path checks, and (c) recommended modeling practices (e.g., 3-D analysis, member capacity checks), and they remain primary references for practice.

2.3 The Alternate Load Path (ALP) method — principles and use

ALP is a largely static, linear or nonlinear, threat-independent procedure in which key vertical elements are computationally removed and the remaining structure is checked for capacity under redistributed loads. ALP's attraction for designers is its conceptual simplicity and its independence from an assumed explosive size/location — it asks, essentially, "if this member is suddenly lost, can the structure find an alternative path to carry the loads?" Many jurisdictions and practitioners apply ALP as the baseline method because it is conservative for many scenarios and straightforward to implement in mainstream structural analysis software. At the same time, ALP is not itself a direct blast-simulation method and does not explicitly represent the time history and impulse characteristics of blast loading.

2.4 Direct, indirect, and energy-based approaches; treatment of dynamics

In contrast to ALP, direct (time-history) methods simulate the actual applied threat (blast or impact) and the resulting dynamic structural response, allowing explicit capture of high-strain-rate behavior, catenary action, and sequential element failures. The indirect (or residual capacity) approaches examine specific residual capacities post-damage. More recently, energy-based ALP formulations and dynamic ALP variants have been proposed to bridge the gap between threat-independent checks and realistic dynamic response; these attempt to include the influence of impact/impulse, rate effects, and the kinetic energy available to drive collapse propagation. Several contemporary studies have revisited ALP assumptions, quantified dynamic amplification factors, and proposed corrections or alternative objective functions to better reflect impulsive loading.

2.5 Numerical methods and advanced modelling techniques

The research literature demonstrates a broad palette of computational tools used in progressive collapse and blast-resistance studies: nonlinear finite element methods (including explicit dynamics), multi-body and discrete element models for fragmentation and progressive failure, simplified frame models for parametric studies, and reduced-order models for probabilistic assessment. Modern explicit solvers (e.g., ABAQUS/Explicit, LS-DYNA) have enabled simulation of complex local failures, contact, and debris interaction under blast; however, such simulations are computationally intensive and sensitive to material models and failure criteria. Comparative studies often find that while ALP provides quick screening, explicit dynamic simulation is required to assess sequence-dependent collapse or to validate innovative mitigation measures.

2.6 Experimental studies and validation efforts

Full-scale and sub-scale experimental campaigns ranging from column removal tests to blast trials — have been used to validate modeling approaches and to reveal important mechanisms such as catenary action in beams, tie forces, and local ductility requirements. Empirical data from experiments underpin calibration of constitutive models and guide recommended tie/ductility provisions in design guidelines. Nevertheless, experimental data remain relatively limited (expensive and hazardous), which constrains broad calibration of high-fidelity numerical models and motivates reliance on conservative ALP checks in many practice contexts.

2.7 Application to blast-resistant design

Blast loads are characterized by very short duration, high amplitude pressure impulses. Designing for progressive collapse under blast has required combining blast-load analysis (to estimate element demands) with structural checks for capacity and redundancy. The ALP method is widely used as a screening tool to ensure that collapse will not disproportionally propagate for a postulated element loss; meanwhile, blast-specific guidance (e.g., FEMA primers and WBDG materials) emphasize layered mitigation: reduce threat effects at the façade, provide local element reinforcement, and ensure global continuity/ties. The literature underscores that ALP alone may not capture threat-dependent phenomena like flying debris, sequential column failures due to asymmetric blast loading, or dynamic amplification in slender elements. Thus hybrid strategies ALP screening plus targeted dynamic simulation for critical scenarios are widely advocated.

2.8 Criticisms, limitations and recent methodological advances

Researchers have identified several limitations of the classical ALP: (1) it is threat-independent and thus may be nonconservative for some blast scenarios (or overconservative for others); (2) it typically employs static removal which neglects dynamic amplification and energy considerations; (3) it depends strongly on the set of removal scenarios chosen; and (4) it can be insensitive to progressive collapse initiated by non-column damage (e.g., beam-column joint failure). To address these issues, the literature reports (a) energy-based ALP metrics that compare available kinetic/strain energy to required energy for failure, (b) hybrid ALP/time-history approaches, (c) improved tie-force calculation methods and design provisions in UFC updates, and (d) probabilistic treatments to quantify risk rather than rely on single deterministic checks. Recent review articles and studies have summarized these advancements, noting that despite methodological progress the practitioner community still relies heavily on ALP due to its simplicity and codified acceptance.

2.9 State of the art — synthesis of findings

The current state of research shows clear complementarities: codes and practice favor ALP for routine design and regulatory compliance, while academic and defense research pushes for more physically realistic direct dynamic and energy-based analyses when the threat (blast, impact) is known or when an asset is critical. Review papers published recently consolidate advances in computational modeling, validation experiments, and code evolution, and they consistently point to three priorities: (1) improved representation of dynamic effects and energy transfer during the initiating event; (2) better characterization and modeling of connections and local failure modes; and (3) integration of probabilistic and performance-based frameworks to support risk-informed design.

2.10 Gaps and future research directions

Key research gaps remain. First, benchmark experimental datasets that span representative blast loads and progressive collapse sequences are still limited; expanding these would enable more confident model validation. Second, multi-hazard and sequential failure (e.g., blast followed by fire or aftershock) needs more study. Third, integrating ALP with probabilistic risk assessment and life-cycle cost analyses would allow more rational trade-offs between redundancy, robustness, and cost. Finally, computationally efficient surrogate models that preserve the salient dynamic and energy transfer features of explicit simulations would enable widespread probabilistic/parametric studies in industry. Researchers are actively pursuing these directions, and recent literature indicates promising methodological hybrids (energy-corrected ALP, targeted direct simulations for bounding scenarios) that can be codified for practice.

3 CONCLUSION AND DISCUSSION

- Progressive collapse remains one of the most critical challenges in the design and assessment of blast-resistant structures. The Alternate Load Path (ALP) method has emerged as a cornerstone technique for evaluating structural robustness under localized damage scenarios, largely due to its conceptual simplicity, threat-independent nature, and compatibility with existing structural analysis tools. This review has synthesized the current state of knowledge, identifying the strengths, limitations, and future directions of ALP as applied to progressive collapse analysis.
- The collective body of literature confirms that ALP provides a practical framework for simulating the loss of critical load-bearing elements and evaluating the redistribution of forces across alternate structural paths. Its implementation in major guidelines and standards (such as GSA and DoD UFC) highlights its relevance in practice. However, despite its widespread adoption, significant limitations remain. The quasi-static formulation of ALP often fails to capture the highly dynamic and nonlinear responses induced by blast loads, leading to possible underestimation of inertia effects, strain-rate sensitivity, and secondary failure mechanisms. Furthermore, the lack of large-scale experimental data hampers validation of numerical predictions and restricts the calibration of simplified models.
- Emerging research trends point toward hybrid methodologies that integrate ALP with nonlinear dynamic analysis, energy-based formulations, and probabilistic risk assessment. Such approaches address many of the deficiencies of traditional ALP and align with the broader movement toward performance-based design. In particular, advances in finite element modeling, multi-hazard simulations, and high-performance computing provide unprecedented opportunities to expand the scope and accuracy of ALP applications. Nevertheless, challenges persist in terms of computational demand, model idealization, and the generalization of results to diverse structural typologies.
- Based on this state-of-the-art review, several outcomes can be emphasized. First, while ALP remains indispensable for design practice, its reliability can be enhanced by embedding it within hybrid or dynamic analysis frameworks. Second, there is a pressing need for more experimental programs, particularly at the component and system level, to validate progressive collapse mechanisms under blast loading. Third,

probabilistic and reliability-based formulations should be integrated into ALP to better capture uncertainties in loading, material properties, and failure progression. Finally, codified provisions require continuous updates to incorporate new insights from research, enabling a gradual transition from prescriptive checks toward robust, performance-based design strategies.

- In summary, the Alternate Load Path method continues to serve as a critical foundation for assessing progressive collapse potential in blast-resistant structures. Its evolution toward hybrid, data-driven, and probabilistic frameworks represents the most promising pathway for future research and practice. By bridging current limitations and aligning with modern performance-based design philosophies, the ALP method can significantly contribute to the development of more resilient, adaptable, and blast-resistant structural systems.

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