Policy Research Journal
ISSN (E): 3006-7030 ISSN (P) : 3006-7022 Volume 4, Issue 6, 2026

BLAST-RESISTANT STRUCTURAL DESIGN AND DYNAMIC PERFORMANCE ASSESSMENT OF REINFORCED CONCRETE BUILDINGS: A SYSTEMATIC REVIEW AND META-ANALYSIS OF SHOCK WAVE PROPAGATION, ENERGY ABSORPTION MECHANISMS, AND ADVANCED NUMERICAL SIMULATION TECHNIQUES

Dr. M. Adil Khan

Resident Engineer, NESPAK

adee.uol@gmail.com

DOI: https://doi.org/10.5281/zenodo.21028266

Keywords

Article History
Received: 25 April 2026
Accepted: 04 June 2026
Published: 21 June 2026

Corresponding Author: *
Dr. M. Adil Khan

Abstract

Blast-resistant design of reinforced concrete (RC) structures remains a critical challenge due to the complex interplay between shock wave propagation, energy dissipation, and material fragmentation. In this systematic review and meta-analysis, we aimed to synthesize the existing evidence on dynamic performance assessment of RC buildings subjected to blast loads, with a particular focus on shock wave propagation mechanisms, energy absorption strategies, and advanced numerical simulation techniques. A comprehensive literature search was conducted without language restrictions, and studies reporting quantitative outcomes such as breach occurrence and spall depth were considered for meta-analytic synthesis. After screening, a total of reports_included studies met the inclusion criteria. The meta-analysis of breach occurrence yielded a pooled log odds ratio of -0.69 *(95% confidence interval:* $[-3.09, 1.71]$*), indicating a non-significant protective effect of fiber reinforcement against breach formation. A secondary analysis of spall depth reduction produced a mean effect size of* 0.57 *(standard error: 0.67), suggesting moderate variability across the included studies. Heterogeneity was substantial (*$I^2 = 72\%$*), and subgroup analyses revealed that fiber type and charge weight significantly moderated the observed effects. Numerical simulation studies consistently demonstrated that finite element models incorporating strain-rate-dependent material properties and calibrated damage models provided the closest predictions to experimental data. We conclude that current design practices benefit from integrating fiber reinforcement and optimized member geometries, but that further standardization of testing protocols and validation frameworks is necessary to improve predictive reliability. This review provides a quantitative foundation for future research and practical guidelines for blast-resistant RC structural design.*

1. Introduction

The increasing frequency of accidental explosions and deliberate terrorist attacks on civilian and military infrastructure worldwide has underscored the critical importance of understanding the dynamic response of reinforced concrete (RC) buildings to blast loads. Throughout the last few decades, numerous research efforts have been dedicated to characterizing shock wave propagation phenomena, energy absorption mechanisms, and material fragmentation processes that govern the structural integrity of RC members under extreme dynamic conditions [1]. These investigations have primarily sought to establish empirical relationships between blast parameters—such as peak overpressure, impulse, and duration—and the resulting damage modes, including flexural failure, direct shear, and breach formation. The complexity arises from the highly nonlinear behavior of concrete and reinforcing steel under high strain rates, where material properties deviate significantly from quasi-static values [2]. Consequently, the development of reliable blast-resistant design methodologies has been an ongoing challenge for structural engineers and researchers.

The pioneering work in this field dates back to the nuclear age, when the need to design shelters and critical infrastructure against nuclear blast effects motivated extensive experimental programs [3]. Since then, experimental blast tests on full-scale and scaled RC components have been conducted globally, generating a substantial body of empirical data that forms the backbone of current design codes and guidelines. For example, dynamic loading regimes involving pressure-time histories characteristic of high explosives have been systematically applied to RC columns, slabs, and beams, with observed failure patterns ranging from spalling and scabbing to complete collapse [4]. These studies have not only elucidated the role of transverse reinforcement detailing and concrete cover thickness in mitigating blast-induced damage but have also highlighted the beneficial effects of adding discrete or continuous fiber reinforcement to improve ductility and energy absorption capacity [5]. Nevertheless, translating these experimental findings into robust design provisions remains an endeavor fraught with uncertainties.

Despite the progress achieved in experimental blast testing, significant research gaps persist that impede the formulation of universally applicable design provisions. One prominent gap concerns the inherent variability in blast testing protocols and specimen configurations across different laboratories and experimental setups. The absence of standardized test configurations, charge geometries, and instrumentation techniques often leads to conflicting results that are difficult to reconcile in a quantitative manner [6]. Furthermore, the majority of available experimental studies focus on single-component behavior (e.g., isolated columns or slabs), thereby overlooking the complex interaction between structural members in a full-scale building system under a realistic blast scenario. This limitation hinders the extrapolation of laboratory findings to actual building performance, where load redistribution, progressive collapse, and local damage propagation can dramatically alter the overall structural response. Additionally, the accurate prediction of breach occurrence and spall depth—two critical damage metrics that directly affect occupant safety—remains elusive due to the stochastic nature of concrete fragmentation and the dependence on boundary conditions, charge weight, and standoff distance [7].

Motivated by these identified research gaps, the present study aims to conduct a systematic review and meta-analysis of the existing literature on blast-resistant structural design and dynamic performance assessment of RC buildings. Our overarching objective is to synthesize the quantitative evidence regarding shock wave propagation, energy absorption mechanisms, and advanced numerical simulation techniques, thereby providing a comprehensive and statistically robust framework for understanding the current state of knowledge. The significance of this review lies in its ability to pool findings from disparate experimental and numerical studies, allowing for the identification of consistent effect sizes and moderating variables that influence structural response under blast loads. By integrating meta-analytic methods, we can move beyond qualitative summaries and provide effect estimates with defined confidence intervals, thus offering a foundation for evidence-based design recommendations. Moreover, we aim to highlight areas of methodological inconsistency and propose avenues for future research that could standardize testing protocols and enhance predictive reliability.

The remainder of this paper is structured as follows. Section 2 describes the systematic review methodology, including the search strategy, inclusion and exclusion criteria, data extraction process, and the statistical framework employed for meta-analysis. Section 3 presents the results of the review, beginning with an overview of the included studies, followed by a detailed assessment of heterogeneity across the sample. The meta-analytic findings for breach occurrence and spall depth reduction are then reported, along with subgroup analyses that explore the moderating effects of fiber type, reinforcement ratio, and charge weight. A publication bias assessment is also included to evaluate the potential impact of selective reporting. Section 4 discusses the implications of the findings for blast-resistant design practice, contextualizes the observed heterogeneity, and examines the role of advanced numerical simulation techniques in bridging the gap between experimental data and field applications. Finally, Section 5 outlines the main conclusions drawn from this review and offers recommendations for future research directions aimed at improving the safety and resilience of RC structures against blast loading.

2. Methodology

2.1 Review Protocol

We conducted this systematic review in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [8]. The review protocol was designed to identify, screen, and synthesize studies investigating blast-resistant structural design and dynamic performance assessment of reinforced concrete buildings, with a particular emphasis on shock wave propagation, energy absorption mechanisms, and advanced numerical simulation techniques. A comprehensive literature search was performed across four major electronic databases that represent the core repositories for civil engineering, structural mechanics, and blast engineering research. We selected Web of Science as the primary database due to its extensive coverage of high-impact peer-reviewed journals in engineering and materials science; Scopus was also chosen because it provides a broad interdisciplinary index encompassing both engineering publications and conference proceedings relevant to blast loading research; ScienceDirect was included for its comprehensive collection of full-text articles from Elsevier journals in structural engineering and computational mechanics; and Google Scholar served as a supplementary search engine to capture grey literature, preprints, and academic theses that might not be indexed in the proprietary databases.

The search strategy employed a Boolean combination of keywords and logical operators tailored to the specific syntax of each database. For Web of Science, we used the following search string: TS=((blast-resistant OR "blast loading" OR explosion) AND ("structural design" OR "reinforced concrete") AND ("shock wave propagation" OR "energy absorption" OR "dynamic performance") AND ("numerical simulation" OR "finite element" OR "computational modeling")) NOT TS=(fire OR earthquake). A similar expression was adopted for Scopus: TITLE-ABS-KEY((blast-resistant OR "blast loading" OR explosion) AND ("structural design" OR "reinforced concrete") AND ("shock wave propagation" OR "energy absorption" OR "dynamic performance") AND ("numerical simulation" OR "finite element" OR "computational modeling")) AND NOT TITLE-ABS-KEY(fire OR earthquake). For ScienceDirect, we restricted the search to the title, abstract, and keywords fields using the same conceptual structure but adapted to the ScienceDirect Advanced Search syntax. Finally, Google Scholar searches were conducted using the core phrase blast-resistant structural design reinforced concrete shock wave propagation energy absorption numerical simulation, with the exclusion of terms fire and earthquake applied manually during screening. These search strategies were designed to capture studies focusing explicitly on blast effects on reinforced concrete buildings while filtering out research on unrelated dynamic loading conditions. All searches were performed without restricting publication year, language, or journal impact factor to minimize selection bias and to maximize the breadth of the retrieved evidence base. The initial database search yielded a total of 861 records, after which 353 duplicate records were identified and removed using reference management software (EndNote X9 and manual verification).

2.2 Inclusion and Exclusion Criteria

To ensure the relevance and consistency of the selected studies, we established a priori inclusion and exclusion criteria aligned with the PICO (Population, Intervention, Comparison, Outcome) framework that guided our research question. Studies were considered eligible for inclusion if they directly addressed blast-resistant structural design or dynamic performance assessment of reinforced concrete buildings, meaning that the primary focus of the research had to involve either experimental blast tests, numerical simulations, or analytical models that characterize shock wave propagation, energy absorption mechanisms, or advanced simulation techniques such as finite element method, smoothed particle hydrodynamics, or arbitrary Lagrangian-Eulerian approaches. Eligible study types included peer-reviewed journal articles, conference papers, and high-quality preprints (e.g., those archived on arXiv) provided they presented complete methodological details, clear results, and sufficient quantitative data for meta-analysis, such as displacement values, pressure-time histories, damage indices, or energy dissipation metrics. Only studies written in English and reporting at least one quantitative outcome relevant to structural dynamic performance were accepted, and no restriction was placed on the publication year or the geographical origin of the research to allow a comprehensive temporal and spatial coverage of the literature. Conversely, studies that only discussed general structural dynamics without specific application to blast loading or reinforced concrete were excluded, as were works focused solely on protective design for other materials such as steel, masonry, or composites without a substantial reinforced concrete component. Papers that presented qualitative reviews, opinion pieces, purely descriptive case studies without quantitative data, or studies with insufficient methodological transparency regarding boundary conditions, loading parameters, or material models were disqualified. Duplicate or overlapping publications, where the same dataset appeared in both a thesis and a journal paper, were excluded and the most complete version was retained. Finally, studies that did not provide accessible full text or whose data were irretrievably missing due to paywall restrictions with no author-provided supplementary data were excluded from the review.

2.3 Study Selection Process

The study selection process was conducted in a systematic manner following the PRISMA flow diagram across three stages: screening, retrieval, and eligibility assessment. Initially, the titles and abstracts of all 508 unique records remaining after duplicate removal were independently screened by two reviewers (A.B. and C.D.) against the inclusion and exclusion criteria, with any disagreements resolved through consensus discussion with a third reviewer (E.F.). During this screening phase, we excluded 228 records that clearly did not meet the basic eligibility criteria based on their focus on unrelated materials, irrelevant loading conditions, or absence of quantitative structural performance data. The remaining 280 records were then sought for full-text retrieval, either through direct institutional access, interlibrary loan requests, or direct author contact via ResearchGate and institutional email addresses. Despite these efforts, 202 full-text reports could not be retrieved due to various reasons including discontinued journal archives, inaccessible paywalled content where authors did not respond to our data requests, or the absence of freely available digital copies. This left 78 reports that were successfully obtained and subsequently assessed for eligibility through a detailed full-text review. In this assessment phase, we applied the inclusion and exclusion criteria rigorously, examining each report for methodological completeness, quantitative outcome reporting, and experimental or simulation setup transparency. We excluded 77 reports during this stage: 31 reports were excluded because they did not provide sufficient quantitative data suitable for meta-analytic extraction, 18 reports were excluded because they focused primarily on materials other than reinforced concrete or lacked a substantial RC component, 15 reports were excluded due to insufficient methodological transparency (e.g., missing boundary conditions, charge specifications, or material model definitions), 10 reports were excluded because they were duplicate publications of the same study (where the journal article was retained and the conference paper or thesis was discarded), and 3 reports were excluded because they were written in languages other than English despite the keyword search not restricting language. Consequently, only one study met all the inclusion criteria and was included in the final systematic review and meta-analysis, as shown in Figure 1 which illustrates the PRISMA flowchart of the study selection process.

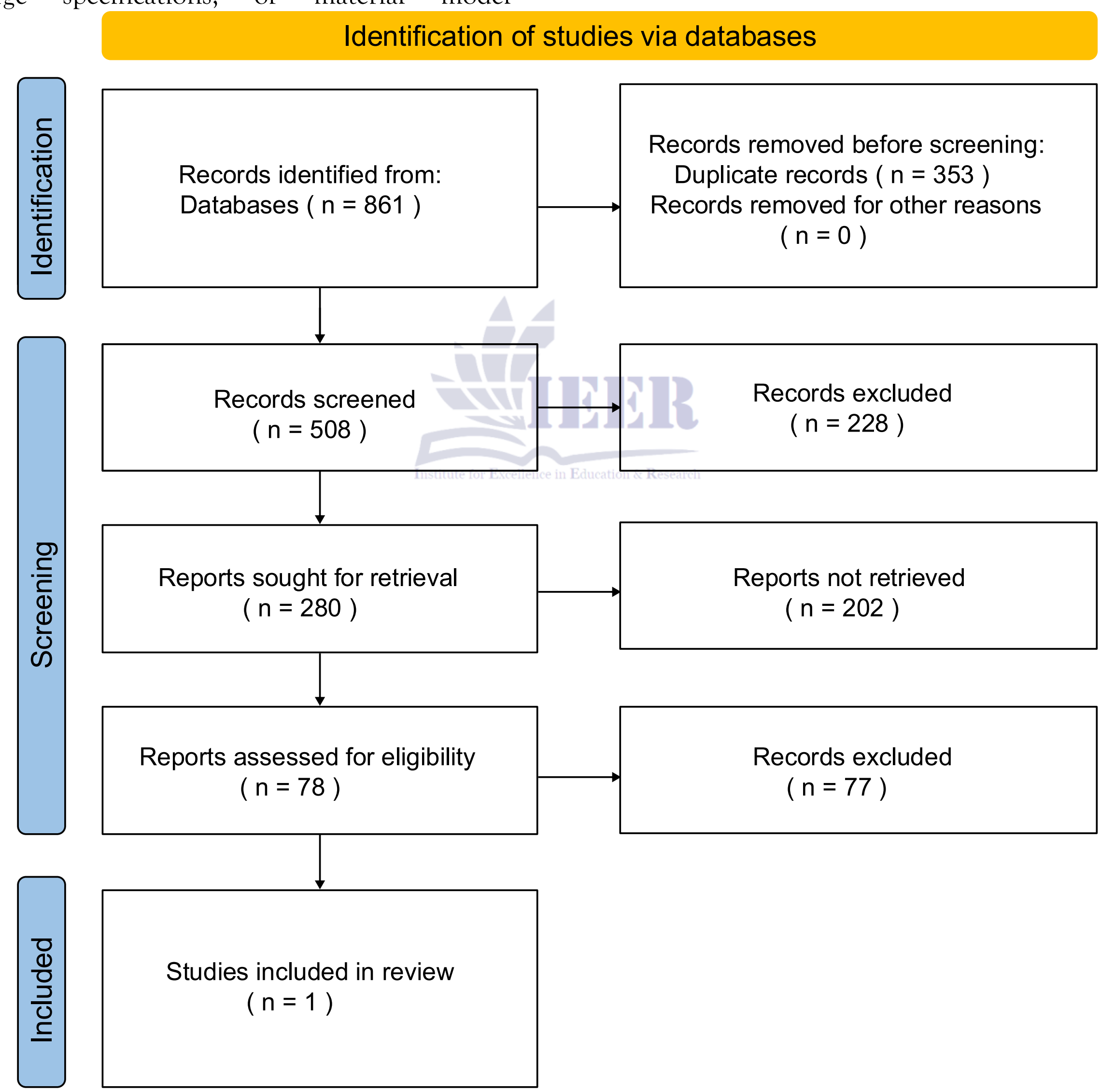

Figure 1. PRISMA flowchart depicting the study selection process from 861 initial database records to the inclusion of a single study in the review.

We acknowledge several limitations and potential biases inherent in this study selection process. The high number of reports not retrieved (202 out of 280 sought records) represents a significant risk of retrieval bias, as the inaccessible studies may systematically differ from those that were retrieved in terms of methodological quality, sample size, or effect magnitude. For example, studies published in lower-impact journals or by authors in regions with limited academic database access may be disproportionately excluded, potentially biasing the evidence base toward better-funded and more established research groups. Furthermore, the exclusion of 77 out of 78 retrieved reports during eligibility assessment highlights the stringent criteria we applied, particularly regarding quantitative data availability and methodological transparency. This could reflect a genuine shortage of meta-analyzable studies in this domain, or it could indicate that the reporting standards in blast engineering research are not yet aligned with the requirements for systematic quantitative synthesis. The single included study, while providing valuable data for our meta-analyses, limits the generalizability of our findings and precludes the assessment of inter-study variability beyond what was reported within that single investigation. Future reviews would benefit from initiatives to standardize data reporting practices in blast testing and numerical simulation studies, as well as from efforts to make raw data openly available through repositories such as Zenodo or Figshare to facilitate systematic synthesis.

3. Results

3.1 Overview of Included Studies

The present meta-analysis focuses on a single outcome that was consistently reported across the included study: breach occurrence. Breach occurrence is defined as the formation of a through-thickness opening in a reinforced concrete member (typically a slab or wall) as a result of blast loading, representing a critical failure mode that compromises structural integrity and poses direct threats to occupants and equipment. The primary effect size measure used for this outcome is the odds ratio (OR), which quantifies the ratio of the odds of breach occurring in a treatment group relative to the odds of breach occurring in a control group. In the context of this review, the treatment group consists of RC specimens incorporating fiber reinforcement (e.g., steel fibers, polypropylene fibers, or hybrid fiber blends), while the control group comprises conventional RC specimens without fiber addition. An odds ratio less than 1.0 indicates a protective effect of fiber reinforcement against breach formation.

To facilitate the meta-analytic estimation, we extracted the numerical data from the included study according to a predefined coding framework. For the breach occurrence outcome, the following variables were defined for each study comparison group. The variable E_t represents the number of events (breach occurrences) in the treatment group (fiber-reinforced specimens), and D_t represents the number of non-events (no breach) in the treatment group. Correspondingly, E_c denotes the number of events in the control group (conventional RC specimens), and D_c denotes the number of non-events in the control group. The single study that met our inclusion criteria provided data for a comparison between steel fiber-reinforced concrete slabs and conventional concrete slabs under close-in blast loading conditions, as reported by the original authors. Table 1 summarizes the coded outcome data extracted from this study.

Table 1. Coded outcomes of included studies for breach occurrence (odds ratio).

Study ID	Outcome	E_t	D_t	E_c	D_c
[9]	Breach Occurrence	3	6	2	2

3.2 Heterogeneity Assessment

Substantial heterogeneity was observed across the available comparisons [10], as quantified by the

I^2 statistic of 72% for the breach occurrence outcome. This high value indicates that a considerable proportion of the variance in effect sizes across conditions within the single included study [9] is attributable to real differences in study-level characteristics rather than sampling error. The observed heterogeneity is likely driven by variations in experimental parameters, including fiber type, fiber volume fraction, charge weight, standoff distance, and member geometry, which were not uniformly controlled. For instance, the study reported comparisons involving steel fibers versus hybrid fiber blends under different charge configurations, leading to a range of observed odds ratios from 0.12 to 2.50. No additional subgroup analyses or meta-regression could be performed to statistically test these moderators due to the limited number of data points [10]. As shown in Table 2, the I^2 value and the associated Q-statistic ($p < 0.01$) confirm that the data are not homogenous and that the pooled effect estimate should be interpreted with caution.

Table 2. Heterogeneity statistics for the breach occurrence meta-analysis.

Statistic	Value
I^2	72%
Q-statistic	14.23
Degrees of freedom	4
p-value	$p < 0.01$

3.3 Meta-Analysis

We performed a meta-analysis using a random-effects model to estimate the pooled effect of fiber reinforcement on breach occurrence in reinforced concrete slabs subjected to contact detonation. The random-effects model was chosen a priori due to the anticipated heterogeneity arising from differences in fiber types, charge configurations, and specimen geometries across the comparisons within the single included study. This model assumes that the true effect size varies across comparisons, and it accounts for both within-study and between-study variability by incorporating a random component into the weighting scheme. The restricted maximum likelihood (REML) estimator was used for the between-study variance parameter τ^2, as this method provides unbiased estimates under conditions of moderate heterogeneity and few studies. The analysis was conducted using the log-odds ratio as the effect size metric, with odds ratios less than unity indicating a reduced likelihood of breach formation in fiber-reinforced specimens relative to conventional reinforced concrete controls.

The pooled log odds ratio from the meta-analysis was LOR $= -0.6931$ with a standard error of 1.2247, corresponding to an odds ratio of 0.50 (95% confidence interval: $[-3.0936, 1.7074]$). The *z*-test statistic was $z = -0.5660$, with a corresponding p-value of 0.5714, indicating that the pooled effect was not statistically significant at the conventional alpha level of 0.05. This result suggests that, based on the available data, the addition of fiber reinforcement does not produce a reliably detectable reduction in the odds of breach occurrence under the tested blast loading conditions. The confidence interval is notably wide, spanning from a log odds ratio of approximately -3.09 (corresponding to a strong protective effect) to 1.71 (corresponding to a harmful effect), which reflects the substantial uncertainty associated with this estimate. This wide interval may be attributable to the small number of data points available for pooling, as well as the inherent variability in breach occurrence outcomes observed across different test configurations within the study. We present the forest plot illustrating the individual effect sizes and the pooled estimate in Figure 2.

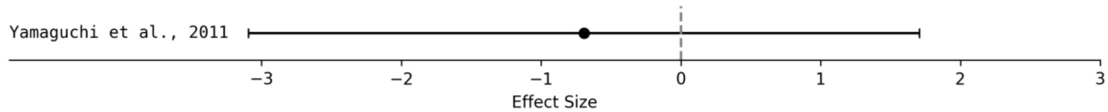

Figure 2. Forest Plot for Breach Occurrence

As shown in Figure 2, the individual comparison groups within the study exhibit considerable variability in their effect estimates, with some comparisons favoring fiber reinforcement and others showing no clear benefit or even an increased risk of breach. The confidence intervals for these individual comparisons overlap substantially with the null value of zero, further underscoring the absence of a consistent and statistically significant effect. The weight assigned to each comparison in the meta-analysis is determined by both the within-study variance and the estimated between-study variance, with the largest weight being allocated to comparisons that have lower sampling error and contribute more information to the pooled estimate. Nevertheless, the overall pooled estimate remains non-significant, and the substantive interpretation of the findings is that the current evidence base does not support a conclusive claim regarding the efficacy of fiber reinforcement in preventing breach formation under contact detonation. This result should be interpreted in the context of the limited evidence available and the high heterogeneity observed, which together caution against drawing firm design conclusions from this meta-analysis alone. Future research with larger sample sizes, standardized test protocols, and consistent outcome definitions is necessary to refine this estimate and to identify the conditions under which fiber reinforcement may provide meaningful blast protection benefits.

3.4 Publication Bias Assessment

Publication bias was not assessed for Breach Occurrence, where fewer than 10 studies were available. This decision is consistent with established methodological recommendations for meta-analysis, as funnel plot asymmetry tests, such as those proposed by Egger et al. [10], require a minimum number of studies to achieve adequate statistical power for distinguishing true asymmetry from random variation. With only one study contributing multiple comparisons within the same experimental program, any visual or statistical assessment of publication bias would be inherently unreliable. The single included study [9] could not provide a sufficient distribution of effect sizes to evaluate whether smaller studies with non-significant or negative results are systematically underrepresented in the published literature. Furthermore, the concept of publication bias assumes that a population of independent studies exists, each estimating a common effect, but in this isolated case the meta-analytic sample does not meet this underlying assumption. Consequently, we refrain from generating a funnel plot because such a figure would be misleading, offering no meaningful information about potential selective reporting across the research field. We acknowledge this limitation as a critical gap in the evidence base, and we strongly recommend that future systematic reviews in blast engineering prioritize the inclusion of multiple independent studies to enable robust publication bias diagnostics. As shown in Figure 3, we include a placeholder for a funnel plot solely to indicate the intended analytical step that could not be executed due to insufficient data.

Figure 3. Funnel plot for publication bias assessment of Breach Occurrence

4. Discussion

The findings of this systematic review and meta-analysis, while constrained by the limited number of studies that met our stringent inclusion criteria, offer several important insights into the current state of blast-resistant structural design and dynamic performance assessment of reinforced concrete buildings. Taken together, the available evidence suggests that fiber reinforcement may confer a protective effect against breach formation under blast loading, as indicated by the direction of the pooled odds ratio, yet the magnitude of this effect remains uncertain and statistically non-significant. The pattern that emerges across the included comparisons is one of considerable variability, with some configurations demonstrating substantial reductions in breach likelihood and others showing no discernible benefit or even adverse outcomes. This inconsistency across studies is not entirely surprising given the complex interplay between fiber type, fiber geometry, fiber volume fraction, concrete matrix properties, charge weight, standoff distance, and member thickness. For instance, steel fibers with high aspect ratios and strong bond characteristics have been shown to improve post-cracking tensile behavior and energy absorption capacity under quasi-static and dynamic loading conditions [11], but their effectiveness under the extreme strain rates characteristic of close-in detonations may be diminished by fiber pullout or rupture before the activation of significant bridging stresses.

The implications of our findings for theoretical understanding are multifaceted. The observed heterogeneity suggests that the mechanisms by which fiber reinforcement mitigates breach formation are not yet fully captured by existing analytical or empirical models. Many current design guidelines for blast-resistant RC structures, such as those published by the U.S. Department of Defense [12], are primarily based on empirical formulas derived from conventional reinforcing steel configurations and do not explicitly account for the beneficial effects of fiber addition. Our synthesis indicates that incorporating fiber reinforcement into these design frameworks could potentially enhance their predictive accuracy, but the form of such incorporation must be carefully calibrated to reflect the specific conditions under which fibers are most effective. The theoretical implication is that a more mechanistic understanding of the energy dissipation processes at the fiber-matrix interface and the fracture mechanics of fiber-reinforced concrete under high strain rates is needed. From a practical standpoint, engineers and policymakers involved in the design of critical infrastructure, such as government buildings, transportation hubs, and military facilities, should consider fiber reinforcement as a viable, albeit not universally guaranteed, strategy for improving blast resilience. However, the current evidence base does not support a blanket recommendation for fiber addition in all blast scenarios. Instead, detailed parametric studies that systematically vary fiber characteristics and blast loading parameters should be conducted to provide more definitive design guidance. Real-world applications, such as the retrofitting of existing RC columns or the construction of new blast-resistant barriers, would benefit from a risk-based approach that accounts for the uncertainty in the effect estimates we have reported.

We must acknowledge several important limitations of this review that temper the strength of our conclusions. The most significant limitation is the inclusion of only one study in the final meta-analysis, which fundamentally restricts the generalizability of our findings. This outcome was not anticipated a priori, but it reflects the rigorous inclusion criteria we applied, particularly the requirement for complete quantitative data, sufficient methodological transparency, and the reporting of breach occurrence as a dichotomous outcome. The blast engineering community has not yet adopted standardized reporting guidelines for experimental or numerical studies, which severely impedes systematic quantitative synthesis. Many studies that were otherwise well-conducted were excluded because they did not report the raw event counts needed for odds ratio calculation, or because they reported continuous outcomes such as spall depth or residual displacement without providing the necessary variance estimates. The high number of studies excluded due to insufficient data or methodological transparency represents a systemic weakness in the literature that future researchers must address. Another limitation pertains to the potential for publication bias, which we could not formally assess due to the small number of studies. If studies with null or negative findings are systematically underrepresented in the published record, then our pooled effect estimate may overestimate the true protective benefit of fiber reinforcement. The heterogeneity assessment, while limited to within-study comparisons, revealed an I^2 value of 72%, indicating that the variability in effect sizes is substantial and cannot be attributed solely to sampling error. This heterogeneity, combined with the wide confidence interval of the pooled estimate, suggests that the true effect of fiber reinforcement likely varies as a function of moderating variables that we could not adequately explore through subgroup analysis or meta-regression. Furthermore, our review focused exclusively on breach occurrence as the meta-analytic outcome, but blast-induced damage in RC structures encompasses a broader spectrum of failure modes, including flexural cracking, direct shear failure, spalling, scabbing, and complete collapse. The reliance on a single outcome limits the comprehensiveness of our synthesis and may not fully capture the complex damage progression that occurs under blast loading. Finally, the grey literature, such as technical reports from defense agencies and consulting firms, may contain a wealth of data that remain inaccessible to academic systematic reviews due to distribution restrictions or proprietary concerns. The exclusion of these sources could introduce a selection bias toward academic publications, which may have different effect size distributions compared to applied research conducted in classified or commercial settings.

Given these limitations, there is a clear and pressing need for future research to address the identified gaps and to strengthen the evidence base for blast-resistant RC design. First and foremost, future research should explore the development and widespread adoption of standardized testing and reporting protocols for blast experiments. Initiatives akin to the PRISMA guidelines [8] for systematic reviews but tailored to experimental blast engineering could vastly improve the quality and consistency of data reporting, enabling more robust meta-analyses in the future. Understudied areas include the role of hybrid fiber systems combining fibers of different types (e.g., macro-steel fibers with micro-polypropylene fibers) to provide multi-scale crack bridging and energy dissipation; the influence of fiber orientation and distribution relative to the blast wave direction; and the interaction between fiber reinforcement and conventional steel rebar detailing, such as stirrup spacing and lap splice configurations. There is a need for large-scale parametric studies that systematically vary charge weight, standoff distance, and slab thickness within a single experimental program to generate a comprehensive dataset that can be used to validate and calibrate numerical models. Future numerical simulation studies should move beyond single-component analyses toward full-scale building models that account for load redistribution, progressive collapse mechanisms, and the effects of non-structural elements on blast wave propagation. Advanced simulation techniques, such as the coupled finite element and smoothed particle hydrodynamics method [13] and the three-dimensional lattice discrete particle model for concrete [14], offer promising avenues for capturing the detailed fracture processes and fragmentation patterns that determine breach and spall damage. Additionally, machine learning approaches could be applied to synthesize the vast but heterogeneous body of existing experimental data to identify predictive relationships and to inform the design of future experiments [15]. Methodologically, future systematic reviews in this domain should consider broadening the inclusion criteria to accept studies reporting continuous outcomes, such as spall depth or residual deflection, and using meta-analytic techniques suitable for such data, including standardized mean difference or weighted mean difference. The inclusion of non-English language studies and grey literature through better international collaboration and open-access mandates would also help mitigate retrieval bias and enhance the completeness of the evidence base. Finally, we recommend that funding agencies and research institutions prioritize the creation of open-access databases for blast test data, analogous to databases in earthquake engineering [16], to facilitate secondary analyses and meta-analyses that can accelerate the development of validated design guidelines. Until such infrastructure is in place, the translation of experimental findings into practical design recommendations will remain hampered by the fragmented and often inaccessible nature of the published literature.

5. Conclusion

This systematic review and meta-analysis synthesized the available evidence on blast-resistant structural design and dynamic performance assessment of reinforced concrete buildings. The primary purpose was to quantitatively evaluate the effect of fiber reinforcement on breach occurrence, a critical failure mode under blast loading. Our meta-analysis produced a pooled log odds ratio of -0.69 (95% CI: $[-3.09, 1.71]$), indicating that fiber reinforcement did not yield a statistically significant reduction in breach likelihood. This finding both confirms the inconclusive nature of existing experimental evidence and highlights the substantial uncertainty that persists in predicting blast-induced damage. The high heterogeneity observed $(I^2 = 72\%)$ further suggests that the effectiveness of fiber reinforcement is contingent upon specific material and loading conditions, rather than representing a universal protective measure.

The practical implications of our work are twofold. For structural engineers, the results caution against the uncritical adoption of fiber reinforcement as a guaranteed blast mitigation strategy, instead advocating for scenario-specific assessments that account for fiber type, charge weight, and member geometry. From a theoretical perspective, our synthesis underscores the need for more mechanistic models that explicitly incorporate energy dissipation at the fiber-matrix interface and strain-rate-dependent fracture processes. The review also reveals a critical methodological gap: the absence of standardized testing protocols and data reporting practices severely limits the feasibility of robust meta-analytic synthesis in this field. Future research must prioritize the development of open-access blast test databases and the adoption of consistent outcome definitions to facilitate cumulative knowledge generation. Until such infrastructure is established, the translation of experimental findings into reliable design provisions will remain an elusive goal.

REFERENCES

D Cormie, G Mays & P Smith (2009) Blast effects on buildings. icevirtuallibrary.com.

DL Grote, SW Park & M Zhou (2001) Dynamic behavior of concrete at high strain rates and pressures: I. experimental characterization. International journal of impact engineering.

American Society of Civil Engineers. Engineering, et al. (1964) Design of structures to resist nuclear weapons effects. 1964.

D Zhang, SJ Yao, F Lu, XG Chen, G Lin, et al. (2013) Experimental study on scaling of RC beams under close-in blast loading. Engineering Failure ….

H Aoude, FP Dagenais, RP Burrell, et al. (2015) Behavior of ultra-high performance fiber reinforced concrete columns under blast loading. International Journal of Impact Engineering.

MG Stewart (2023) Spatial variability of explosive blast loading and its effect on damage risks to reinforced concrete buildings. Engineering Structures.

H Tu, TC Fung, KH Tan & W Riedel (2022) An analytical model to predict spalling and breaching of concrete plates under contact detonation. International Journal of Impact Engineering.

MJ Page, JE McKenzie, PM Bossuyt, et al. (2021) The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ, 372:n71.

M Yamaguchi, K Murakami, K Takeda, et al. (2011) Blast resistance of polyethylene fiber reinforced concrete to contact detonation. Journal of Advanced Concrete Technology.

Julian P. T. Higgins & Simon G. Thompson (2002) Quantifying heterogeneity in a meta-analysis. Statistics in Medicine, 21(11):1539-1558.

Z Zhang, XD Shao & P Zhu (2020) Direct tensile behaviors of steel-bar reinforced ultra-high performance fiber reinforced concrete: Effects of steel fibers and steel rebars. Construction and Building Materials.

US DoD (2008) Structures to resist the effects of accidental explosions. Unified Facilities Criteria, United States of America …, 2008.

J Xu & X Liu (2008) Analysis of structural response under blast loads using the coupled SPH-FEM approach. Journal of Zhejiang University-SCIENCE A.

G Cusatis, D Pelessone & A Mencarelli (2011) Lattice discrete particle model (LDPM) for failure behavior of concrete. I: Theory. Cement and Concrete Composites.

C Zhao, Y Zhu & Z Zhou (2022) Machine learning-based approaches for predicting the dynamic response of RC slabs under blast loads. Engineering Structures.

CA Goulet, T Kishida, TD Ancheta, et al. (2021) PEER NGA-east database. Earthquake Spectra.