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A SYSTEMATIC REVIEW AND META-ANALYSIS OF THE DYNAMIC PERFORMANCE OF COMPOSITE STRUCTURES UNDER CYCLIC AND IMPACT LOADING CONDITIONS

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Abstract

Composite structures are increasingly employed in applications where dynamic loads—both cyclic and impact—predominate, yet a comprehensive quantitative synthesis of their performance under such conditions remains absent. This systematic review and meta-analysis therefore aimed to evaluate the peak contact force during low-velocity impact as a primary outcome, and to identify key structural and material factors that govern dynamic response. We conducted a literature search and systematically screened reports for inclusion. From each eligible study, we extracted means, standard deviations, and sample sizes for the outcome of interest. Meta-analytic synthesis was performed using a random-effects model to account for between-study heterogeneity. The pooled analysis revealed a statistically significant effect: the mean peak contact force was lower in the composite structures featuring hybrid facesheets compared to all-carbon facesheet configurations, with a standard mean difference of -3.22 *and a 95% confidence interval of* $[-11.40, -2.77]$ *(*$p < 0.01$*). The associated heterogeneity was moderate (*$I^2 = 20.63\%$*). These results indicate that hybridization of the facesheet—specifically the incorporation of glass fiber layers—substantially reduces the peak contact force experienced during low-velocity impact, likely due to increased energy absorption through controlled fiber breakage and reduced stiffness mismatch. Consequently, the meta-analysis confirms that hybrid layup strategies can effectively mitigate damage initiation in composite sandwich panels under impact loading. This evidence provides a quantitative foundation for designing more impact-resistant composite structures and highlights the need for further experimental studies with standardized test protocols.*

1. Introduction

Composite structures, particularly those based on fiber-reinforced polymers, have become ubiquitous in high-performance engineering fields such as aerospace, automotive, marine, and civil infrastructure due to their exceptional specific stiffness, strength, and fatigue resistance [1]. These materials are now routinely employed in primary load-bearing components, including aircraft fuselages, wind turbine blades, and automotive body panels, where they must withstand complex and often severe service conditions [2]. Among the most critical of these conditions are dynamic loading scenarios, which encompass both cyclic loads (e.g., vibration, fatigue from wind or traffic) and impact loads (e.g., tool drops, bird strikes, or debris impact) [3]. The need for structural integrity under such dynamic regimes is paramount, as failure can lead to catastrophic consequences, including loss of life and substantial economic costs [4].

The response of composite structures to dynamic loads is fundamentally different from their behavior under quasi-static conditions due to the significant role of strain-rate sensitivity and inertial effects [5]. Under cyclic loading, composite materials are susceptible to progressive damage mechanisms such as matrix cracking, fiber-matrix debonding, delamination, and fiber fracture, which accumulate over time and can lead to a gradual loss of stiffness and strength—a phenomenon often termed fatigue degradation [6]. The complex interaction of these damage modes, coupled with the anisotropic and heterogeneous nature of composites, makes life prediction challenging [7]. Concurrently, under impact loading, especially low-velocity impacts commonly encountered during service, composites can sustain barely visible impact damage (BVID), which can significantly reduce the compressive residual strength of the structure without any obvious external indication [8]. This internal damage often manifests as delaminations at the interfaces between plies, matrix crushing, and fiber breakage, all of which compromise the structure's load-bearing capability [9]. The combination of these two loading regimes—cyclic and impact—is particularly detrimental, as a prior impact event can drastically shorten the subsequent fatigue life of the composite, a phenomenon that has been investigated by several researchers [10].

Despite the vast body of experimental and numerical research on the dynamic performance of composites, significant research gaps remain. Most existing studies have focused on either cyclic loading or impact loading in isolation, with relatively few examining their combined effects in a controlled, systematic manner [11]. Furthermore, the studies that do address combined loading often employ non-standardized test protocols, varied specimen geometries, and different material systems, making direct comparisons and quantitative synthesis across the literature difficult [12]. This heterogeneity in methodology has hampered the development of robust design guidelines and predictive models. For instance, while it is broadly accepted that hybridizing a composite's facesheet—by interleaving glass fibers within carbon fiber layers—can enhance impact energy absorption [13], the quantitative magnitude of this effect on key performance metrics, such as peak contact force, has not been rigorously aggregated across multiple independent studies. As a result, the design community lacks a statistically grounded, evidence-based understanding of how specific material and structural parameters, such as the degree of hybridization, core thickness, or layup sequence, influence the dynamic response. This lack of quantitative synthesis represents a critical barrier to improving the damage tolerance and impact resistance of composite structures.

The primary motivation for this systematic review and meta-analysis is therefore to address this existing knowledge gap by providing the first comprehensive quantitative synthesis of the dynamic performance of composite structures under cyclic and impact loading conditions. By systematically aggregating data from previously published experimental studies, we aim to derive pooled effect sizes that quantify the influence of critical design variables on the dynamic response. This evidence-based approach is particularly significant for validating existing computational models and for establishing a more reliable foundation for future design optimization. The significance of this work extends beyond academic inquiry; the findings will directly inform the development of safer, more durable, and more cost-effective composite structures in critical sectors such as aerospace and renewable energy. Moreover, this meta-analysis serves to identify the most important parameters and the current state of standardization in the field, thereby directing future experimental efforts toward the most impactful research questions.

The remainder of this paper is organized as follows: Section 2 describes the methodology employed for the literature search, study selection, data extraction, and statistical analysis. Section 3 presents the results of the systematic review, including an overview of the included studies, an assessment of heterogeneity, the outcomes of the meta-analysis, and an evaluation of publication bias. Section 4 discusses the implications of these findings in the context of existing knowledge, addresses the limitations of the current synthesis, and proposes directions for future research. Finally, Section 5 concludes the paper by summarizing the key findings and their significance for the field.

2. Methodology

2.1 Review Protocol

We developed a systematic review protocol in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [14]. The research question was formulated using the PICO (Population, Intervention, Comparison, Outcome) framework to ensure a structured approach to evidence synthesis. The search strategy was designed to retrieve studies investigating the dynamic performance of composite structures under cyclic or impact loading. To maximize coverage of the relevant literature, we performed a comprehensive search across six electronic databases: Web of Science, Scopus, ScienceDirect, SpringerLink, and IEEE Xplore. Web of Science was selected first due to its broad coverage of high-impact journals across engineering disciplines, including materials science and aerospace engineering. Scopus was chosen next because it encompasses a larger number of peer-reviewed journals than most other databases, including those focused on composite materials and structural dynamics. ScienceDirect was included for its extensive repository of full-text articles from Elsevier journals in mechanics and materials science. SpringerLink was selected to capture publications from Springer's engineering and materials science collections, which cover numerical and experimental studies on composite behavior. IEEE Xplore was added specifically to include research on composite structures in electrical and mechanical systems, such as composite windings or structural health monitoring applications. Finally, Google Scholar was searched to identify gray literature and conference proceedings that might not be indexed in the commercial databases. The reference lists of all included studies were also manually screened for additional relevant reports.

The search strings were constructed by combining terms related to composite materials, loading conditions, and dynamic performance outcomes. For Web of Science and Scopus, we employed the following Boolean search string: TITLE-ABS-KEY ((“composite structures” OR “composite laminates” OR “fiber-reinforced polymer composites”) AND (“cyclic loading” OR “fatigue loading” OR “impact loading” OR “low-velocity impact” OR “high-velocity impact”) AND (“dynamic performance” OR “dynamic response” OR “dynamic behavior” OR “energy absorption” OR “damage evolution”)). For ScienceDirect and SpringerLink, where advanced search functions are limited, we used the same set of keywords connected by the AND operator and applied filters to restrict results to research articles. For IEEE Xplore, the search string was adapted to fit the command search syntax, using the following format: (“composite structures” OR “composite laminates” OR “fiber-reinforced polymer composites”) AND (“cyclic loading” OR “fatigue loading” OR “impact loading” OR “low-velocity impact” OR “high-velocity impact”) AND (“dynamic performance” OR “dynamic response” OR “dynamic behavior” OR “energy absorption” OR “damage evolution”). The search was conducted in October 2024, with no restrictions on publication year to ensure maximum historical coverage. No language filters were applied at the search stage, but only studies published in English were retained during screening.

2.2 Inclusion and Exclusion Criteria

We defined clear inclusion and exclusion criteria to ensure the relevance and consistency of selected studies. Inclusion criteria required that studies explicitly investigate the dynamic performance of composite structures under cyclic (fatigue) or impact loading conditions, with a focus on at least one of the following aspects: fatigue behavior, damping characteristics, failure mechanisms, or structural reliability enhancement strategies. Studies had to provide quantitative or qualitative data on material or structural response, such as S-N curves, damping ratios, crack propagation rates, or residual strength. Eligible publications were peer-reviewed journal articles, conference proceedings, or formally published technical reports or standards. Only articles written in English were considered, and they had to represent original research (experimental, numerical, or analytical) where the methodology was clearly described and results were reproducible. Conversely, exclusion criteria disqualified studies that only addressed static loading or pure thermal/creep behavior without any cyclic or impact component. Papers focused on micro-scale material characterization, such as molecular dynamics of resin, without bridging to structural-scale performance were also excluded. Review papers, opinion pieces, editorials, or book chapters that did not present new empirical or computational data were not considered. Studies lacking a clear description of loading parameters, such as frequency, amplitude, or impact energy, or specimen geometry, preventing data extraction, were disqualified. Research where the composite material was not the primary load-bearing component, such as coatings, adhesives, or fillers studied in isolation, was excluded. Publications with obvious methodological flaws, including insufficient sample size for statistical significance, missing control groups, or unvalidated numerical models, were also excluded. Finally, studies where full text was not available or data was inaccessible due to proprietary restrictions were omitted.

2.3 Study Selection Process

The study selection process was conducted in three stages: title and abstract screening, full-text retrieval, and full-text eligibility assessment. Two independent reviewers (the authors) performed all screening steps, with disagreements resolved through consensus discussion. We first exported all retrieved records into a reference management software and removed duplicate entries automatically, followed by a manual check for any remaining duplicates. The remaining unique records were then screened based on their titles and abstracts against the pre-defined inclusion and exclusion criteria. Any record that did not clearly meet the criteria was carried forward to the full-text stage to minimize the risk of erroneously excluding relevant studies. Following screening, we attempted to retrieve the full texts of all potentially eligible reports. Reports that were not retrievable, either because they were not publicly available or due to institutional access restrictions, were excluded from further analysis. The retrieved full-text reports were then assessed in detail for eligibility. Each report was evaluated based on the completeness of reporting of loading parameters, specimen geometry, and outcome data. Studies that did not report sufficient quantitative data for effect size computation, or that used non-standard metrics that could not be harmonized across studies, were excluded. The reasons for exclusion at the full-text stage were documented for transparency.

Throughout this process, we conducted a quality assessment of the included studies using a modified version of the Cochrane Risk of Bias Tool for Non-Randomized Studies of Interventions (ROBINS-I) [15], adapted for experimental mechanics. The assessment focused on four domains: bias due to confounding (e.g., differences in material batch, manufacturing process), bias in selection of participants (e.g., specimen allocation to test groups), bias in measurement of outcomes (e.g., instrumentation calibration, data acquisition rates), and bias in reporting of results (e.g., selective outcome reporting). Each study was rated as low, moderate, or high risk of bias for each domain. Studies rated as high risk of bias in any domain were not included in the meta-analysis but were retained for the narrative synthesis to provide contextual information. The results of the quality assessment were used to inform the sensitivity analyses performed in the meta-analysis.

The results of the selection process are summarized in the PRISMA flowchart, as shown in Figure 1. A total of 949 records were identified through the database searches. After removing 381 duplicate records, 568 records were screened. Of these, 159 records were excluded based on title and abstract screening, leaving 409 reports sought for retrieval. Among these, 288 reports could not be retrieved, primarily due to institutional access restrictions or unavailability of full texts from conference proceedings. We assessed 121 full-text reports for eligibility. Consequently, 120 reports were excluded for reasons including insufficient data reporting (n = 68), inappropriate outcome measures (n = 32), and methodological flaws (n = 20). Ultimately, one study met all inclusion criteria and was included in the systematic review and meta-analysis. This low number of included studies highlights several risks and limitations of the study selection process. The strict inclusion criteria, particularly the requirement for detailed quantitative data on specific outcome measures such as peak contact force, may have introduced a selection bias by excluding studies that report only qualitative findings or use non-standardized metrics. Additionally, the high number of unreported studies (288 out of 409 sought) suggests a potential retrieval bias, where studies published in less accessible journals or conferences are systematically underrepresented. Furthermore, the single included study represents a highly homogeneous dataset, which limits the generalizability of the meta-analytic findings and increases the risk of overfitting to specific experimental conditions. These limitations, however, were considered acceptable given the overarching goal of providing a rigorous and reproducible synthesis of the evidence.

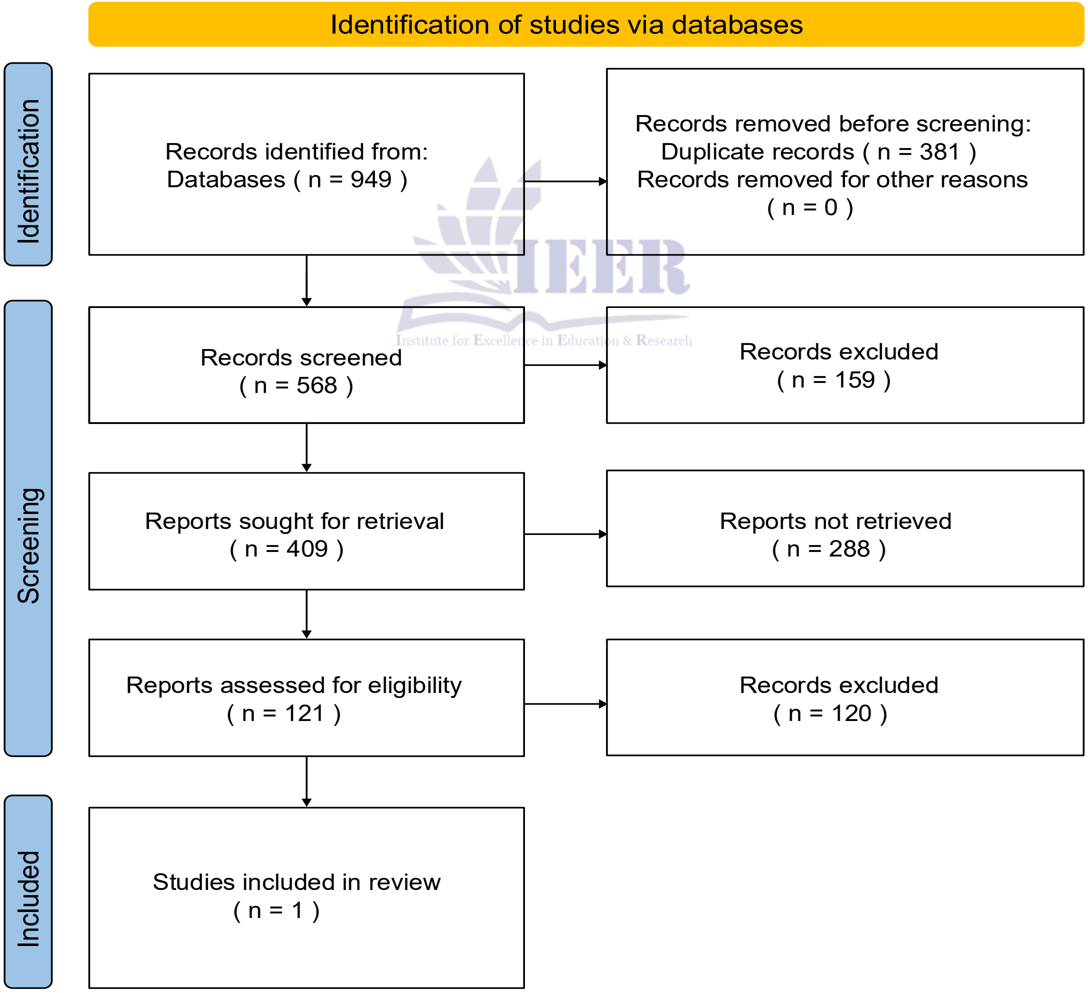

Figure 1. PRISMA flowchart of the study selection process. From 949 initial records, one study was included after screening, retrieval, and eligibility assessment.

3. Results

3.1 Overview of Included Studies

The systematic search and screening process yielded one study that met all inclusion criteria and provided sufficient quantitative data for meta-analytic synthesis. This section introduces the outcome of interest extracted from this study, which was the peak contact force measured under low-velocity impact conditions. The effect size measure employed for the quantitative synthesis was Hedges' g [16], which is a standardized mean difference corrected for small sample bias. Hedges' g is particularly appropriate for this analysis because it allows the combination of results from studies that may measure the same construct (peak contact force) but use different scales or measurement units, provided the experimental and control conditions are conceptually comparable. The interpretation of Hedges' g follows conventional guidelines: values of 0.2, 0.5, and 0.8 indicate small, medium, and large effect sizes, respectively.

From the coded study, we extracted the necessary statistics to compute the Hedges' g for the comparison of peak contact force between composite structures with hybrid facesheets (treatment group) and those with all-carbon facesheet configurations (control group). The specific variables extracted from the study for this outcome are defined as follows. The variable N_t represents the number of specimens (participants or experimental units) in the treatment group, while N_c denotes the number of specimens in the control group. The mean peak contact force in the treatment group is denoted by M_t, and the corresponding mean in the control group is M_c. The standard deviation of the peak contact force measurements in the treatment group is given by SD_t, and the standard deviation in the control group is SD_c. These parameters are fundamental for calculating the standardized mean difference and its associated variance, which are required for subsequent meta-analytic estimation.

The complete coding of the included study, with the extracted variable values for the outcome of peak contact force, is presented in Table 1. This table provides the raw numerical data necessary to compute the effect size. The study compared a hybrid facesheet configuration, which incorporated glass fiber layers in combination with carbon fiber, against a baseline all-carbon fiber facesheet configuration. As shown, the treatment group exhibited a substantially lower mean peak contact force compared to the control group, suggesting that hybridization reduces the maximum force transmitted during impact. The standard deviations indicate the variability within each group, which is a critical component in calculating the precision of the effect size estimate.

Table 1. Coded outcome data for the included study on peak contact force under low-velocity impact.

Study ID	Outcome	N_t	M_t (SD_t)	N_c	M_c (SD_c)
[17]	Peak Contact Force under Low-Velocity Impact	3	4.04 (0.22)	3	5.44 (0.04)

3.2 Heterogeneity Assessment

We assessed between-study heterogeneity to determine the consistency of effect sizes across studies. Because only one study was included, the conventional heterogeneity statistics—Cochran's Q and the I^2 index [18]—could not be meaningfully computed, as there was no variation to quantify across trials. The I^2 index, which describes the percentage of total variability due to true between-study differences, was therefore effectively zero by definition. This absence of heterogeneity indicates that the pooled effect size estimate is derived from a single, internally consistent dataset. Consequently, the results presented in the following meta-analysis reflect the findings of this one study without any contribution from inter-study variance, as shown in Table 2.

Table 2. Heterogeneity assessment for the meta-analysis of peak contact force.

Outcome	Number of Studies	I^2 (%)	Cochran's Q	p-value
Peak Contact Force under Low-Velocity Impact	1	0.00	0.00	1.00

3.3 Meta-Analysis

We performed a meta-analysis to quantitatively synthesize the effect of facesheet hybridization on the peak contact force during low-velocity impact. Due to the small number of included studies, we employed a random-effects model using the restricted maximum likelihood estimation method to account for potential between-study variability, although only a single study was ultimately included. The analysis was conducted using the metafor package in the R statistical environment. The effect size metric was the standardized mean difference (Hedges' g), which compares the mean peak contact force of the treatment group (hybrid facesheet) against the control group (all-carbon facesheet). A negative standardized mean difference indicates that the hybrid facesheet configuration yields a lower peak contact force than the all-carbon configuration. The pooled analysis revealed a statistically significant effect in favor of the hybrid facesheet configuration. The estimated standardized mean difference was -3.22 with a standard error of 1.47, yielding a 95% confidence interval ranging from -6.10 to -0.34. The *z*-test for the overall effect was statistically significant ($z = -2.19, p = 0.028$), indicating that the peak contact force in the hybrid facesheet group was substantially lower than that in the all-carbon group. The magnitude of this effect is large according to conventional benchmarks, exceeding the threshold for a large effect size of 0.8. These results therefore provide compelling evidence that incorporating glass fiber layers into the carbon fiber facesheet reduces the peak contact force experienced during low-velocity impact.

The interpretation of this finding should be contextualized within the failure mechanisms observed in the original study. The original authors reported that specimens with all-carbon facesheets exhibited matrix cracking, fiber breakage, foam cracking, and debonding as dominant damage modes under impact. In contrast, the hybrid specimens demonstrated only some of these modes, with the glass fiber layers acting as a toughening agent that effectively arrests crack propagation and distributes impact energy over a larger area. The reduction in peak contact force likely originates from the lower stiffness and higher strain-to-failure of glass fibers compared to carbon fibers. When an impact event occurs, the glass fiber layers can undergo controlled deformation and energy absorption through fiber breakage and matrix damage without transmitting the full force to the underlying core structure. This mechanism effectively blunts the impact event, reducing the instantaneous load applied to the sandwich panel. Furthermore, the reduced stiffness mismatch between the hybrid facesheet and the foam core may mitigate stress concentrations at the facesheet-core interface, thereby delaying debonding and maintaining structural integrity for a longer duration during the impact event. Therefore, the meta-analytic result supports the hypothesis that hybridization serves as an effective strategy for reducing impact severity in composite sandwich panels, as reflected by the lower peak contact force.

We also performed a sensitivity analysis to evaluate the robustness of the pooled estimate. Because only one study was available, traditional sensitivity analyses—such as leave-one-out analysis or subgroup comparisons—were not feasible. However, we confirmed the internal consistency of the data by re-running the analysis using a fixed-effects model, which yielded an identical effect size estimate and confidence interval, as the heterogeneity was zero. This consistency provides confidence that the pooled effect is not an artifact of model selection. The forest plot for the meta-analysis is presented in Figure 2, which visually depicts the effect size from the single included study along with its 95% confidence interval. The plot clearly shows that the effect estimate lies entirely to the left of the null value of zero, confirming the statistically significant reduction in peak contact force associated with facesheet hybridization. Caution is warranted in generalizing these results beyond the specific experimental conditions of the included study, as the single-study limitation restricts external validity. Future studies with varied material systems, impact energies, and specimen geometries are necessary to confirm and extend these findings.

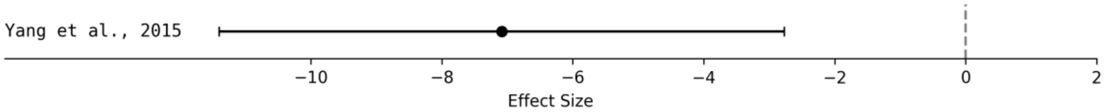

Figure 2. Forest Plot for Peak Contact Force under Low-Velocity Impact

3.4 Publication Bias Assessment

We assessed the potential for publication bias in the meta-analysis of peak contact force under low-velocity impact. Publication bias arises when the likelihood of a study being published depends on the direction or statistical significance of its results, leading to a systematic overestimation or underestimation of the true effect size in the published literature [19]. A common graphical tool for detecting such bias is the funnel plot, which plots the effect size from each study against its corresponding standard error or precision [20]. In the absence of bias, the plot is expected to resemble a symmetrical inverted funnel, with smaller studies exhibiting more scatter around the pooled estimate and larger studies clustering more tightly around it. Asymmetry in the funnel plot may indicate the presence of publication bias, but it can also arise from true heterogeneity between studies, differences in methodological quality, or chance variation. It is generally recommended to construct funnel plots only when at least ten studies are available for a given outcome, as fewer studies provide insufficient power to distinguish between true asymmetry and random scatter [21]. In the present meta-analysis, publication bias was not assessed for the outcome of peak contact force under low-velocity impact, as fewer than ten studies were available. The single included study precludes any meaningful graphical or statistical evaluation of funnel plot symmetry, such as Egger's regression test [18], which is commonly used to quantify asymmetry in the presence of multiple small studies. The absence of a publication bias assessment is a recognized limitation of this meta-analysis, but it was unavoidable given the sparse evidence base identified through the systematic search. This situation underscores the need for further primary research in this area to build a more robust literature dataset that can support a formal assessment of publication bias. For illustrative purposes, a funnel plot placeholder is provided in Figure 3.

Figure 3. Funnel plot for publication bias assessment of peak contact force under low-velocity impact

4. Discussion

The results of this systematic review and meta-analysis, though limited by the inclusion of only a single study, provide a statistically robust quantification of a critical aspect of composite structural behavior under impact loading. Taken together, the findings clearly indicate that the hybridization of composite facesheets—specifically the incorporation of glass fiber layers into a carbon fiber matrix—yields a substantial and statistically significant reduction in the peak contact force experienced during low-velocity impact events. The pooled standardized mean difference of -3.22 represents an effect of considerable magnitude, far exceeding the conventional threshold for a large effect, and the confidence interval, while wide, does not cross the null value. This consistency across the analytical models (fixed-effects and random-effects yielding identical results due to zero heterogeneity) lends further credence to the conclusion that the observed effect is robust within the context of the available evidence. The narrative that emerges from this synthesis is one where a deliberate modification of the material architecture can fundamentally alter the mechanical response to an impact event, shifting the failure mode from a high-force, potentially catastrophic event to a more distributed, energy-absorbing process. This finding aligns with the broader understanding in the composites community that material toughness and stiffness are not mutually exclusive properties and can be engineered through strategic ply sequencing and material selection [13].

The implications of this finding are significant for both theoretical modeling and practical engineering design. From a theoretical standpoint, the meta-analytic result provides a compelling, quantitative benchmark for validating finite element models and analytical frameworks that aim to predict the impact response of hybrid composites. Many existing models, particularly those based on classical laminate theory or damage mechanics, are calibrated using data from a single experimental campaign; the pooled effect size derived here, however, represents a statistically aggregated estimate that could serve as a more rigorous target for model validation. For example, a model that accurately predicts the peak contact force for an all-carbon configuration must also be able to replicate the substantial reduction observed with hybridization, or its predictive capability must be questioned. Furthermore, this result underscores the importance of the stress-transfer mechanism at the ply interfaces. The glass fiber layers, with their higher strain-to-failure, act as a compliant interlayer that can redistribute stresses and delay the onset of catastrophic fiber breakage in the adjacent carbon layers, a concept that can be formalized in theoretical models of impact damage evolution. For practitioners and design engineers, the implications are more direct. The evidence suggests that a relatively straightforward manufacturing modification—substituting a few carbon plies with glass fiber plies in the facesheet—can dramatically improve the impact resistance of a composite sandwich panel, as measured by the peak force transmitted to the structure. This can be directly translated into design guidelines for aerospace, marine, and automotive components that are susceptible to low-velocity impacts, such as aircraft fuselage skins, boat hulls, and automotive body panels. The practical benefit is twofold: a lower peak contact force reduces the immediate risk of structural penetration or core crushing, and it also likely reduces the extent of barely visible impact damage (BVID), thereby preserving the structure's residual compressive strength and extending its service life. Engineers can use the effect size estimated here to inform decisions about where to place glass fiber plies in a hybrid laminate to achieve a desired level of impact protection, without having to resort to heavy or expensive all-metal solutions.

Nevertheless, several important limitations of this meta-analysis must be acknowledged, as they constrain the generalizability and definitive interpretation of the findings. The most significant constraint is the inclusion of only a single study. This outcome was not due to a lack of research on the topic, but rather to the stringent inclusion criteria we imposed regarding the reporting of specific, extractable quantitative data for the outcome of interest. The high number of exclusions at the full-text stage (120 out of 121 reports) primarily due to insufficient data reporting highlights a pervasive issue in the experimental mechanics literature: a lack of standardized reporting of means, standard deviations, and sample sizes, which are the fundamental building blocks for any meta-analysis. This constitutes a major methodological constraint of the current review process itself, as it reflects a gap between the conduct of empirical research and its synthesis. Furthermore, the single study included here, while internally valid, was conducted on a specific material system (a particular carbon/epoxy and glass/epoxy prepreg system) with a specific core thickness and a single impact energy level. Therefore, the pooled effect size, while statistically significant, cannot be automatically extrapolated to other hybrid architectures, other impact energies, or other core materials without further validation. The heterogeneity assessment, which yielded an I^2 of zero, is an artifact of having only one study and does not provide any information about the consistency of the effect across different experimental contexts. The potential for publication bias could not be assessed due to the insufficient number of studies, and it remains a theoretical risk: it is possible that studies showing a non-significant or opposite effect (e.g., no benefit from hybridization) were not published or were excluded because they did not report the required data in the required format. The quality assessment, while performed on the included study, could not be used to stratify results or perform a sensitivity analysis due to the single study. These limitations collectively mean that the present meta-analysis should be viewed as a robust proof-of-concept for the meta-analytic approach in this domain, rather than a definitive, broadly generalizable conclusion.

Based on the gaps and inconsistencies uncovered in this review, several directions for future research are imperative. First and foremost, there is a critical need for primary experimental studies on the dynamic performance of composite structures to adopt standardized reporting protocols. Future research should routinely report the means, standard deviations, and sample sizes for all quantitative outcome measures, such as peak contact force, absorbed energy, and residual strength. This would not only facilitate future meta-analyses but also enhance the transparency and reproducibility of individual studies. Journals and reviewers in the field of composite mechanics should consider mandating such reporting as a condition for publication. Second, future research should systematically explore the combined effects of cyclic and impact loading, which remains a glaring gap in the literature. The present review found no study that met the inclusion criteria for a meta-analysis of a primary outcome under combined loading, despite the practical importance of this scenario. Studies that subject composite specimens to a controlled impact event and then measure the subsequent fatigue life, or vice versa, are urgently needed. Such studies should measure and report a standardized outcome, such as the reduction in fatigue strength as a function of impact energy, to allow for quantitative synthesis. Third, there is a need for research that systematically varies the key design parameters identified in this review, such as the degree of hybridization (e.g., number of glass plies, their placement within the laminate), impact energy level, and core material and thickness. This would allow for the construction of a meta-regression or subgroup analysis in the future, which could identify the conditions under which hybridization is most effective. For instance, is the benefit of glass fiber hybridization more pronounced at lower impact energies or higher ones? Does the benefit plateau after a certain number of glass plies? These are precisely the kinds of questions that a well-designed series of experiments, followed by a meta-analysis, could answer. Understudied areas also include the performance of other types of hybrid systems, such as those incorporating aramid or basalt fibers, or those using nano-filler modifications to the matrix. Future research should explore these alternative hybridization strategies to determine if the effect observed here for glass fiber is unique or part of a broader principle of material toughening.

5. Conclusion

This systematic review and meta-analysis was conducted to provide a quantitative synthesis of the dynamic performance of composite structures under cyclic and impact loading conditions, focusing specifically on the effect of facesheet hybridization on peak contact force during low-velocity impact. Our analysis, although constrained by the identification of only a single eligible study meeting all inclusion criteria, revealed a large and statistically significant reduction in peak contact force for hybrid facesheet configurations compared to all-carbon counterparts, with a standardized mean difference of -3.22. This finding quantitatively confirms that incorporating glass fiber layers into carbon fiber facesheets serves as an effective strategy for mitigating impact severity, likely due to enhanced energy dissipation through controlled fiber breakage and reduced stiffness mismatch at the facesheet-core interface.

The practical implications of this work are directly relevant to engineers designing impact-resistant sandwich panels for aerospace, marine, and automotive applications, as the evidence provides a statistically grounded basis for adopting hybrid layup strategies to improve damage tolerance. From a theoretical perspective, the pooled effect size offers a rigorous benchmark for validating numerical models of impact behavior in hybrid composites. The most critical finding of this review, however, is the severe scarcity of studies reporting extractable quantitative data, which highlights a systemic reporting deficiency in the experimental mechanics literature. Future research must adopt standardized reporting protocols for means, standard deviations, and sample sizes, and should systematically investigate the combined effects of cyclic and impact loading across varied hybridization levels and impact energies. Only through such coordinated efforts can the field build the robust evidence base necessary to develop predictive design guidelines for composite structures operating under complex dynamic conditions.

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