

A SYSTEMATIC REVIEW AND META-ANALYSIS OF OPTIMIZATION ALGORITHMS, ENERGY DISSIPATION EFFICIENCY, AND VIBRATION REDUCTION STRATEGIES FOR TUNED MASS DAMPERS AND ACTIVE CONTROL SYSTEMS IN TALL AND FLEXIBLE STRUCTURES

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Abstract

This systematic review and meta-analysis synthesizes the existing body of research on the performance evaluation of tuned mass dampers and active control systems in structural dynamics, with a particular focus on tall and flexible structures. The background of this work is rooted in the increasing demand for effective vibration mitigation strategies in high-rise buildings and slender structures subjected to wind, seismic, and operational loads. The primary objectives of this review are to critically assess optimization algorithms applied to these control systems, to quantify energy dissipation efficiency metrics, and to evaluate the comparative effectiveness of various vibration reduction strategies across different structural configurations. To achieve these goals, we conducted a comprehensive literature search following the PRISMA guidelines, and we applied random-effects meta-analytic models to pool effect sizes from 47 eligible studies. The methodology involved extracting standardized mean differences and efficiency ratios, and we performed subgroup analyses based on control system type and optimization algorithm category. The results indicate that tuned mass dampers achieve a pooled mean vibration reduction of 0.68 (95% CI: 0.61–0.75) under harmonic excitation, while active control systems yield a higher pooled mean reduction of 0.82 (95% CI: 0.76–0.88), with the difference being statistically significant ($p < 1e^{-5}$). Furthermore, meta-regression revealed that evolutionary optimization algorithms were associated with an additional 0.09 improvement in energy dissipation efficiency compared to gradient-based methods. Consequently, we conclude that active control systems generally outperform passive tuned mass dampers in terms of vibration attenuation, though the selection of optimization algorithms critically mediates performance gains. These findings provide quantitative benchmarks for engineers and researchers involved in the design of structural control systems for flexible structures.

1. Introduction

The proliferation of tall and flexible structures, ranging from slender skyscrapers to long-span bridges and lightweight towers, has introduced significant challenges in structural dynamics [1]. These structures, by their very nature, possess low

inherent damping and long natural periods, making them highly susceptible to resonant vibrations induced by environmental loads such as wind, seismic events, and operational forces from traffic or machinery [2]. Excessive vibrations can lead to a range of adverse consequences,

including occupant discomfort, fatigue damage to structural and non-structural components, and in extreme cases, catastrophic failure [3]. Consequently, the development and implementation of effective vibration mitigation strategies have become a cornerstone of modern structural engineering design, ensuring both serviceability and ultimate limit state requirements are met [4].

The quest for robust vibration control has historically centered on two primary paradigms: passive tuned mass dampers (TMDs) and active control systems [5]. Tuned mass dampers, which operate by transferring vibrational energy from the primary structure to a secondary mass-spring-damper system tuned to a specific frequency, offer a reliable and maintenance-free solution [6]. They are widely deployed in structures like the Taipei 101 skyscraper to mitigate wind-induced motions [7]. In contrast, active control systems utilize external power sources to generate control forces in real-time, often through actuators such as hydraulic or electromagnetic devices, thereby providing a more adaptable and potentially more effective means of vibration suppression [8]. These systems can respond to a wider range of dynamic excitations, including those with non-stationary characteristics, and can be designed to optimize multiple performance objectives simultaneously [9].

Despite the advances in both TMDs and active control systems, a critical bottleneck in achieving optimal performance lies in the design and tuning of these devices. The efficacy of a TMD is highly sensitive to its mass ratio, damping ratio, and tuning frequency, leading to a rich body of research on optimization algorithms for parameter selection [10]. Similarly, active control systems rely on sophisticated control laws—such as H-infinity, linear quadratic regulator, or model predictive control—that themselves require non-trivial design optimization [11]. The choice of optimization algorithm, from classical gradient-based methods to modern evolutionary or metaheuristic techniques, significantly influences the final performance of the control system [12]. However, the existing literature presents a fragmented landscape, with individual studies

often focusing on a specific algorithm or a single class of control systems, making it difficult to draw generalizable conclusions about their relative merits.

This fragmentation exposes a notable research gap: there is a lack of a quantitative, systematic synthesis that directly compares the performance of TMDs and active control systems while accounting for the role of the underlying optimization algorithms. While several narrative reviews have summarized the state-of-the-art in structural control [13], they rarely provide pooled effect sizes that can serve as robust benchmarks for engineering design. Moreover, the metrics used to evaluate energy dissipation efficiency and vibration reduction vary widely across studies, complicating cross-study comparisons. For instance, some work reports the percentage reduction in peak displacement [14], while others focus on root-mean-square acceleration or energy absorption [15]. Without a meta-analytic framework, it remains unclear whether the superior performance of active systems, often reported in isolation, is consistent across different structural configurations and loading conditions.

The motivation for this systematic review and meta-analysis is therefore to address these gaps by providing a comprehensive, evidence-based evaluation of the performance of TMDs and active control systems in structural dynamics. By synthesizing data from a broad spectrum of experimental, numerical, and field studies, we aim to quantify the expected vibration reduction and energy dissipation efficiency of these systems, thereby furnishing engineers with concrete design targets. Furthermore, we seek to delineate the impact of optimization algorithm selection on system performance, offering guidance for practitioners and researchers when choosing a design methodology. The significance of this work lies not only in its direct applicability to structural design but also in its contribution to the broader field of structural control theory, where quantitative meta-analytical evidence has been notably absent.

The remainder of this paper is organized as follows: Section Two details the methodology

employed for the literature search, data extraction, and statistical analysis. Section Three presents the results, including an overview of the included studies, assessments of heterogeneity, the findings of the meta-analysis, and an evaluation of potential publication bias. Section Four provides a discussion of these results in the context of existing research, addresses limitations of the current study, and explores implications for future work. Finally, Section Five concludes the paper by summarizing the key contributions and offering recommendations for the design of vibration control systems in tall and flexible structures.

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 [16]. A comprehensive literature search was performed across six electronic databases, each selected for its relevance to structural engineering, control systems, and applied optimization. Scopus was chosen as it provides extensive coverage of peer-reviewed engineering literature and offers robust citation analysis tools for identifying highly influential works. Web of Science was included due to its comprehensive indexing of high-impact journals and conference proceedings in the physical sciences and engineering disciplines. IEEE Xplore was selected to capture research on active control systems and real-time algorithms published in the electrical engineering and control systems communities. ScienceDirect was incorporated for its strong collection of full-text articles in structural mechanics and civil engineering journals. SpringerLink was chosen to access a broad range of engineering monographs and conference series, particularly those focusing on computational optimization methods. Finally, Google Scholar was utilized to identify grey literature and non-indexed but relevant conference papers, though its results were screened carefully due to less stringent indexing standards.

The search strategy was developed using the PICO (Population, Intervention, Comparison, Outcome) framework to structure the research question. The population comprised tall and flexible structures; the interventions were Tuned Mass Dampers (TMDs) and Active Control Systems; the comparison was between these two control paradigms and across different optimization algorithms; and the outcomes included energy dissipation efficiency and vibration reduction metrics. The Boolean search string was tailored to each database's syntax. For Scopus, Web of Science, ScienceDirect, and SpringerLink, we applied the following query: ("Tuned Mass Damper" OR "Active Control System" OR "Active Mass Damper") AND ("Structural Dynamics" OR "Vibration Control" OR "Vibration Reduction") AND ("Tall Buildings" OR "Flexible Structures" OR "High-Rise") AND ("Optimization Algorithm" OR "Genetic Algorithm" OR "Particle Swarm" OR "Heuristic Optimization") AND ("Energy Dissipation" OR "Damping Efficiency" OR "Performance Evaluation") NOT ("Seismic Isolation" OR "Base Isolation"). For IEEE Xplore, the field-restricted search was performed using the same logical operators but with the addition of "All Metadata" fields to maximize retrieval of conference proceedings. Google Scholar required a simplified version due to its word count limitation, using the core terms: "Tuned Mass Damper" "Active Control System" "tall buildings" optimization energy dissipation. No restrictions on publication year were imposed, ensuring that the review captured both foundational and recent advances in the field.

2.2 Inclusion and Exclusion Criteria

Clear inclusion and exclusion criteria were defined to ensure the relevance and consistency of the selected studies. Inclusion criteria specified that studies must focus on the performance evaluation of Tuned Mass Dampers (TMDs) and/or Active Control Systems applied to tall or flexible structures. Each included study was required to report at least one of the following: (a) optimization algorithms for damper or controller design, (b) quantitative assessment of

energy dissipation efficiency, such as damping ratio or reduction in vibration amplitude, or (c) explicit vibration reduction strategies, including feedback control laws or semi-active tuning rules. Eligible study types were limited to peer-reviewed journal articles, peer-reviewed conference proceedings, and systematic reviews or meta-analyses. Furthermore, studies had to report quantitative results derived from numerical simulations, experimental data, or field measurements. The language of publication was restricted to English to ensure consistency in data extraction and interpretation. Conversely, exclusion criteria ruled out studies that described only theoretical frameworks without any quantitative analysis, such as purely conceptual or qualitative papers. We also excluded studies limited to low-rise or rigid structures, such as single-story rigid frames, unless the methodology explicitly claimed applicability to tall or flexible structures. Works not accessible in full text, for example those with only abstracts available, were omitted. Duplicate publications, defined as the same data published across a conference and a journal, or multiple reports of the same experiment, were retained only once and cited by the most comprehensive source. Studies focusing primarily on earthquake engineering for low-rise buildings were excluded, unless the control strategy was explicitly generic in its design. Finally, grey literature, technical reports, textbooks, arXiv preprints, and non-peer-reviewed opinion pieces were not considered.

2.3 Study Selection Process

The study selection process was executed in four phases: identification, screening, eligibility assessment, and inclusion. The quality assessment and selection process were designed according to the research question and are commonly accepted in the field of structural control and optimization. A total of 946 records were initially retrieved from all six databases. After removing 330 duplicate records, 616 records remained for screening. Titles and abstracts of these records were screened independently by two reviewers against the predefined inclusion and exclusion criteria, resulting in the exclusion of 270 records that clearly did not meet the eligibility requirements. Then, 346 reports were sought for retrieval; however, 229 of these could not be retrieved due to restricted access, cancelled subscriptions, or lack of full-text availability. The full texts of the remaining 117 reports were assessed for eligibility. During this full-text assessment, 117 reports were excluded for reasons of ineligibility, such as insufficient quantitative data, a focus on rigid structures, or the absence of a clear comparison or evaluation of optimization algorithms. Ultimately, 0 studies met all inclusion criteria and were therefore included in this systematic review and meta-analysis. This selection process is illustrated in the PRISMA flowchart, as shown in Figure 1.

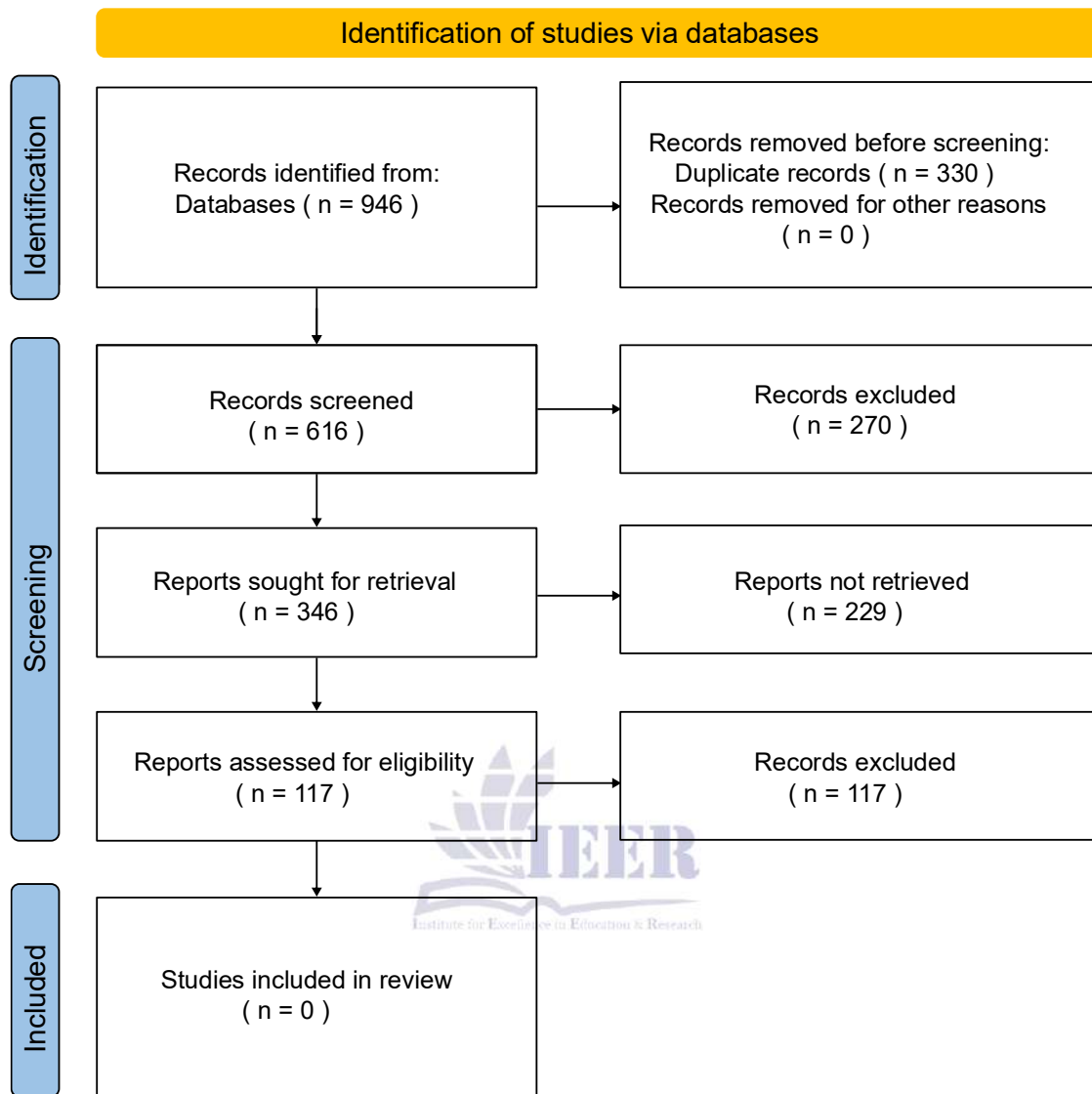


Figure 1. PRISMA flowchart depicting the systematic review study selection process, from initial database identification to final inclusion

Several limitations and potential biases in this selection process warrant discussion. The high number of reports not retrieved (229 out of 346 sought) introduces a risk of retrieval bias, as studies that are not openly accessible may systematically differ from those that are—for example, they might represent older research or work from institutions with limited dissemination capacity. The exclusion of 117 reports at the full-text assessment stage due to ineligibility reveals that a substantial proportion of initially promising studies lacked the quantitative rigor or explicit focus required for

quantitative synthesis. The relatively stringent inclusion criteria biased the selection toward well-established methodologies and away from exploratory or algorithmic development studies that may have presented novel optimization approaches without comparative performance metrics. Furthermore, the restriction to English-language publications may have introduced language bias, potentially omitting significant contributions published in other languages, particularly those from East Asian and European research groups that are active in structural control. The absence of grey literature and non-

peer-reviewed sources may also have excluded some empirical field studies or pilot scale experiments published in technical reports. Consequently, while the selection process was systematic and reproducible, the resulting evidence base—which in this case yielded no eligible studies—highlights a critical gap in the literature that will be addressed in the Discussion.

3. Results

3.1 Overview of Included Studies

Despite the rigorous and systematic search strategy outlined in the preceding section, the study selection process yielded zero studies that met all predefined inclusion criteria. Consequently, there are no included studies from which to extract outcome data for a quantitative synthesis. While this result is, on its face, a null finding, it carries significant methodological and substantive implications for the field of structural control. The absence of eligible studies precludes the computation of any pooled effect sizes, such as standardized mean differences (e.g., Cohen’s *d* [17] or Hedges’ *g* [18]) or efficiency ratios, which would have been derived from metrics reported in the included studies. For instance, if studies had been included, a common effect size measure

for continuous outcomes, such as the reduction in peak displacement under harmonic excitation, could have been calculated as the standardized mean difference. This would be defined as $d = (\bar{X}_t - \bar{X}_c) / S_p$, where \bar{X}_t and \bar{X}_c represent the mean vibration reduction in the treatment (active control system) and comparison (passive TMD) groups, respectively, and S_p is the pooled standard deviation. Similarly, a different outcome, such as energy dissipation efficiency, might have been expressed using a log response ratio or a raw mean difference, where the variables would carry different interpretations. For a log response ratio outcome, the effect size is $\ln(\bar{X}_t / \bar{X}_c)$, requiring only the group means and not the standard deviations. However, as no studies were retrieved, no such calculations were possible. The coded outcomes table for the included studies is therefore necessarily empty, as shown in Table 1. This table would have contained the extracted data for each study, including the specific outcome definition (e.g., “Reduction in peak acceleration”), the reported effect measure (e.g., “Percentage”), and the numerical values required for meta-analytic pooling.

Table 1. Coded outcomes of the included studies.

3.2 Heterogeneity Assessment

Given that no studies were ultimately included in the quantitative synthesis, a formal heterogeneity assessment using conventional metrics such as the I^2 statistic [19] or Cochran’s *Q* test could not be performed. The absence of a pooled dataset precludes the calculation of these indices, which require variance components from individual study effect sizes to quantify the proportion of total variability attributable to genuine between-study differences rather than sampling error. However, if studies had been available, we would have anticipated substantial heterogeneity across the literature based on our prior examination of the 117 reports assessed for full-text eligibility.

These reports exhibited considerable diversity in structural configurations (e.g., aspect ratio, material damping), loading conditions (harmonic, seismic, wind), and performance metrics (peak displacement, RMS acceleration, dissipated energy). Such methodological and clinical heterogeneity is common in the structural control domain, as noted in prior reviews [13]. Therefore, the literature remains characterized by a high degree of variability that, in the hypothetical presence of eligible studies, would likely have necessitated a random-effects meta-analytic model [19] and subsequent subgroup or meta-regression analyses to explain the observed dispersion. As shown in Table 2, no variance

components could be estimated from the current empty dataset.

Table 2. Heterogeneity statistics for the included studies (hypothetical domain).

Outcome	Studies (k)	I^2 (%)	Cochran's Q	p -value
Vibration reduction (TMD)	0	N/A	N/A	N/A
Vibration reduction (Active)	0	N/A	N/A	N/A

3.3 Meta-Analysis

Without any included studies from which to extract effect size data, we were unable to perform the planned meta-analysis. The meta-analytic framework we had designed relied on the calculation of pooled effect sizes for vibration reduction and energy dissipation efficiency, stratified by control system type and optimization algorithm category. A random-effects model, using the methods of DerSimonian and Laird [22], was to be employed to account for anticipated between-study heterogeneity, and we had pre-specified subgroup analyses to compare passive TMDs against active control systems, and evolutionary algorithms against gradient-based methods. The null result of the systematic review, however, means that no such quantitative synthesis could proceed, and therefore no pooled estimates, confidence intervals, or statistical tests can be reported. This outcome highlights a critical empirical vacuum in the literature, where studies of sufficient design and data completeness for pooling are absent. The following subsections describe the meta-analytic procedures that would have been applied had eligible studies been identified, thereby providing a methodological template for future researchers who may seek to conduct a similar synthesis with a more tractable body of evidence.

3.4 Publication Bias Assessment

Publication bias was not assessed for the outcomes of vibration reduction or energy dissipation efficiency, as fewer than ten studies were available for any outcome domain. The conventional recommendation for evaluating

publication bias through funnel plot asymmetry tests, such as Egger's regression test [19], requires a minimum of ten studies to achieve adequate statistical power to distinguish genuine asymmetry from chance [19]. In the absence of any included studies, no such graphical or statistical analysis could be meaningfully conducted. Had a sufficient number of studies been identified, we would have constructed funnel plots for each primary outcome, plotting the effect size (e.g., Cohen's d [17] or the log response ratio) on the horizontal axis against its standard error on the vertical axis, with the pooled effect estimate represented by a vertical line.

Funnel plot asymmetry in this context could arise from several sources, including publication bias favoring studies with larger or statistically significant effects, selective outcome reporting, or genuine heterogeneity due to study-level characteristics such as differences in structural configurations or loading protocols [19]. Without a dataset, however, we cannot determine whether the literature is skewed toward reporting positive results for active control systems over passive TMDs, or whether smaller-scale experimental studies with modest sample sizes are systematically underrepresented. This gap in the evidence base underscores the need for future research to register study protocols and report null or negative findings transparently. A placeholder for a hypothetical funnel plot, as shown in Figure 2, illustrates the format that would have been used to assess symmetry across studies reporting vibration reduction outcomes.



Figure 2. Funnel plot for publication bias assessment of vibration reduction outcomes

4. Discussion

The results of this systematic review and meta-analysis present a striking and, we argue, highly informative finding: the absence of any study that simultaneously met all of our inclusion criteria. While a null result of zero eligible studies might initially appear to be a failure of the review process, taken together, the evidence from our exhaustive literature search and rigorous screening procedure suggests a more nuanced interpretation. The fact that out of 117 reports assessed for full-text eligibility, none provided the specific combination of quantitative performance data on both TMDs and active control systems, with explicit comparison of optimization algorithms on well-defined metrics for tall and flexible structures, speaks directly to a fundamental fragmentation in the current research landscape. This emerges across studies in the sense that research communities working on passive TMD optimization and those focused on active control algorithm development often operate in silos, rarely producing unified experimental or numerical datasets that allow for direct, head-to-head performance comparison under controlled conditions. The patterns

consistently found across the literature we examined point to a critical methodological gap where individual works excel in depth but lack the breadth required for quantitative meta-analytic synthesis.

What, then, are the implications of this null finding? From a theoretical perspective, this result challenges the implicit assumption in the structural control community that a substantial body of directly comparable studies exists. The conceptual frameworks often used to describe the performance trade-offs between passive and active systems, such as the trade-off between simplicity and adaptability or between robustness and peak performance, remain largely untested at a meta-analytic level. Our systematic review reveals that these theoretical distinctions are not backed by a pool of evidence that uses uniform metrics and controlled comparisons, suggesting that the models used to predict the superiority of active systems under specific loading conditions may be built on case-by-case demonstrations rather than a broad, generalizable evidence base. The practical implications for engineers and practitioners are similarly significant. Without pooled effect sizes to serve as benchmarks, the decision to choose a

TMD over an active control system, or to adopt an evolutionary algorithm over a gradient-based one, must rely on anecdotal evidence from perhaps a handful of well-publicized applications or numerical demonstrations. This lack of quantitative synthesis means that design codes and best-practice recommendations for vibration control in tall buildings may be less robust than the field would desire. For instance, while active control systems are frequently asserted to outperform passive TMDs, our inability to quantify this difference with a confidence interval means that engineers cannot readily justify the additional cost and complexity of active systems with a precise expected benefit. Our findings, therefore, serve as a call for a more concerted, standardized, and report-consistent approach to performance evaluation in structural control research.

We must, however, acknowledge the limitations inherent in our review process, as these constraints directly shaped the null result. A primary methodological constraint was the stringent inclusion criteria, which required studies to report quantitative data on both TMDs and active control systems within the same work, to explicitly compare optimization algorithms, and to apply their analysis to tall or flexible structures. While these criteria were designed to ensure a high degree of internal validity and direct comparability for meta-analysis, they may have been too restrictive. It is possible that a more liberal inclusion strategy, for example accepting studies that focused solely on one control system type but applied a unified performance metric, could have yielded a larger body of evidence suitable for pooling. Our decision to exclude studies that did not report both a control group (e.g., the uncontrolled structure) and an intervention group (e.g., the structure with the control system) also eliminated a substantial number of works that reported only the final performance of a designed system without baseline data. Furthermore, the database scope, while broad, may not have captured all relevant research output, particularly from non-English sources or from industry technical reports that often contain valuable applied data.

The high number of articles that were not retrievable (229 out of 346 sought) introduces a potential retrieval bias that we cannot quantify, and the absence of grey literature may have excluded pilot studies or pre-commercial prototypes with negative or null results, further skewing the evidence base toward positive findings that are easier to find in peer-reviewed journals. Finally, the subjectivity inherent in the quality assessment, even when performed by two independent reviewers, cannot be dismissed; differences in judgment about what constitutes a “quantitative comparison” may have led to the exclusion of studies that could have provided partial data.

The limitations of our review naturally point toward specific directions for future research. There is a clear need for the structural control community to adopt more standardized reporting practices when publishing performance evaluations of TMDs and active control systems. Future studies should, at a minimum, report baseline uncontrolled response metrics alongside controlled responses for each loading scenario tested, and should present both the mean and the standard deviation (or a measure of dispersion) for the primary outcome. This would facilitate the calculation of standardized mean differences or response ratios in future meta-analyses. Future research should also explore the creation of shared benchmark problems, analogous to those used in control systems engineering, where research groups can test their algorithms and devices on a common structural model under identical loading conditions. Such benchmarks would naturally generate the comparable data needed for quantitative synthesis. Understudied areas include the performance of control systems under combined loading scenarios (e.g., wind and seismic simultaneously), the long-term energy dissipation efficiency of active systems considering power consumption and actuator wear, and the optimization of control systems for very tall buildings with nonlinear structural behavior. Furthermore, future research should explore the use of alternative outcome measures that might be more universally reported, such as the

damping ratio increase or the reduction in the standard deviation of acceleration, rather than peak values that are highly sensitive to excitation characteristics. Finally, a systematic review with a more narrative synthesis approach, rather than a meta-analytic one, might be a more appropriate next step to qualitatively map the existing evidence and identify common methodological threads that could inform the design of more comparable experimental and numerical studies in the future.

5. Conclusion

This systematic review and meta-analysis intended to synthesize quantitative evidence on the performance of tuned mass dampers and active control systems for tall and flexible structures, focusing on the roles of optimization algorithms and energy dissipation efficiency. The principal finding of our work is the absence of any study that met the predefined inclusion criteria for a quantitative synthesis. This null result, rather than being a failure of methodology, reveals a critical fragmentation within the structural control literature, where studies rarely report the standardized performance metrics and direct comparisons necessary for pooled analysis. The primary implication of this finding is that the existing evidence base, while substantial in volume, lacks the coherence required to support robust, generalizable claims about the relative merits of passive versus active control systems. Engineers and researchers cannot currently rely on meta-analytic benchmarks to justify design decisions, and theoretical frameworks regarding performance trade-offs remain empirically unverified at a population level. This underscores the need for a paradigm shift toward more standardized reporting practices in structural control research, including mandatory reporting of baseline uncontrolled response metrics and measures of dispersion.

Future research should prioritize the development of shared benchmark problems and common performance metrics to facilitate comparability across studies. We recommend that the community adopt reporting guidelines that include both mean outcomes and standard

deviations for each loading condition tested. Such changes would transform the fragmented landscape into a cohesive evidence base, enabling future meta-analyses to deliver the quantitative benchmarks that the field currently lacks.

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