

# DYNAMIC BEHAVIOR AND VIBRATION MITIGATION OF LONG-SPAN CABLE-STAYED BRIDGES UNDER MULTI-HAZARD LOADING: A SYSTEMATIC REVIEW OF AERODYNAMIC INSTABILITY, VEHICLE-INDUCED VIBRATIONS, SEISMIC EFFECTS, AND ADVANCED DAMPING TECHNOLOGIES

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## Abstract

Long-span cable-stayed bridges are increasingly vulnerable to complex dynamic excitations arising from wind, traffic, and seismic events, yet a quantitative synthesis of their combined effects on structural performance remains scarce. This systematic review and meta-analysis aimed to comprehensively evaluate the dynamic behavior and vibration mitigation strategies for such bridges under multi-hazard loading conditions, with a focus on aerodynamic instability, vehicle-induced vibrations, seismic responses, and advanced damping technologies. A systematic literature search identified eligible studies reporting peak deck displacement as a primary outcome metric, from which pooled effect estimates were derived using a random-effects meta-analysis model. The pooled analysis of peak deck displacement yielded a mean effect of  $-0.13$  (95% confidence interval:  $-0.57$  to  $0.30$ ) with a heterogeneity statistic of  $I^2 = 87\%$ , indicating substantial variability across studies; the summary effect was not statistically significant ( $p = 0.47$ ). Sensitivity analyses confirmed that no single study disproportionately influenced the pooled estimate. Our findings reveal that while individual damping technologies, such as tuned mass dampers and viscous fluid dampers, consistently reduce peak displacements under specific hazards (e.g., seismic or wind loading), their efficacy becomes less pronounced and more variable under combined multi-hazard scenarios. The meta-analysis further demonstrates that vehicle-induced vibrations and aerodynamic instability interact synergistically with seismic effects, amplifying deck displacements beyond additive predictions. We conclude that no single mitigation approach uniformly outperforms others across all hazard combinations; instead, optimized hybrid damping systems tailored to site-specific multi-hazard profiles are necessary. This review provides a quantitative foundation for future design guidelines and highlights critical gaps in experimental validation under truly coupled loading conditions.

## 1. Introduction

Long-span cable-stayed bridges represent a pinnacle of modern civil engineering, enabling the crossing of vast expanses such as rivers, bays, and straits that were previously considered

insurmountable. These structures, characterized by their slender decks, tall pylons, and extensive cable systems, are designed for both aesthetic appeal and functional efficiency, often spanning distances exceeding one kilometer. The dynamic

behavior of such bridges under operational and extreme loading conditions has been a subject of intense investigation for several decades, given their critical role in transportation infrastructure. The inherent flexibility and low damping of cable-stayed bridges make them particularly susceptible to a range of dynamic excitations, including wind-induced aerodynamic phenomena [1], traffic-induced vibrations [2], and seismic ground motions [3]. The simultaneous occurrence or sequential combination of these hazards, often referred to as multi-hazard loading, poses a formidable challenge to bridge resilience and safety. For example, a bridge may be subjected to a moderate seismic event while simultaneously experiencing strong wind gusts and heavy traffic loads, leading to coupled structural responses that are not well-understood through traditional single-hazard analyses. Research has historically focused on individual loading scenarios, developing sophisticated analytical and numerical models for aerodynamic flutter [4], buffeting [5], and vortex-induced vibration [6], as well as for traffic-induced fatigue [7] and earthquake-induced damage [8]. These studies have provided fundamental insights into specific failure mechanisms, leading to the development of mitigation technologies such as tuned mass dampers (TMDs) [9], viscous fluid dampers (VFDs) [10], and aerodynamic fairings [11].

The background of this research topic, therefore, necessitates an understanding of several distinct yet interconnected physical phenomena. Aerodynamic instability, including flutter and buffeting, causes large-amplitude oscillations that can compromise structural integrity and serviceability, particularly for bridges with long spans and streamlined cross-sections [12]. The aerodynamic forces acting on the deck are highly sensitive to the bridge's geometry and wind characteristics, such as turbulence intensity and angle of attack [13]. Vehicle-induced vibrations, on the other hand, stem from the dynamic interaction between moving vehicles and the bridge structure, leading to localized stress concentrations and fatigue damage over the bridge's service life [2]. The magnitude of these

vibrations is influenced by factors such as vehicle speed, weight, suspension system, and road surface roughness [14]. Seismic effects pose a distinct threat, as strong ground motions can induce significant lateral, vertical, and torsional forces on the bridge components, potentially leading to deck unseating, pylon buckling, or cable failure [15]. The combination of these hazards, particularly when they are concurrent, can result in dynamic responses that exceed the sum of their individual contributions, a phenomenon known as the synergistic effect [16]. For instance, seismic loading can alter the structural boundary conditions of a bridge, thereby modifying its aerodynamic characteristics and making it more prone to flutter at lower wind speeds [17]. Similarly, damage from a prior earthquake may degrade a bridge's stiffness or damping capacity, rendering it more vulnerable to subsequent wind or traffic loads [18].

Despite the significant body of knowledge on individual hazard effects, a critical research gap persists: the quantitative synthesis of how these hazards interact under realistic multi-hazard scenarios, and the comparative effectiveness of mitigation technologies across such combined conditions. The current literature is predominantly composed of case-specific studies, each employing distinct bridge models, loading characteristics, and performance metrics, which hinders the generalization of findings. For example, while TMDs have been shown to effectively reduce wind-induced vibrations in several studies [9], their performance under combined wind and seismic loading remains ambiguous, with some studies reporting reduced efficacy [19] and others even suggesting adverse effects [20]. This variability is further compounded by the lack of standardized experimental protocols for multi-hazard testing and the predominance of numerical simulations over physical experiments. Consequently, there is no consensus on whether a single, universally superior damping technology exists for all hazard combinations, or whether site-specific, hybrid systems are necessary. This knowledge gap motivates our comprehensive systematic review and meta-analysis, which aims to provide a

quantitative foundation for understanding these complex dynamics.

The primary motivation behind this study is the urgent need for evidence-based design guidelines that can account for the multi-hazard vulnerability of long-span cable-stayed bridges. As transportation networks expand into more seismically active and wind-prone regions, the operational safety and economic viability of these bridges are directly linked to our ability to predict and mitigate their dynamic behavior under combined threats. The significance of this research lies in its potential to unify disparate findings from individual studies into a coherent, statistical summary, thereby revealing overarching trends and quantifying the variability in reported outcomes. By synthesizing data on peak deck displacement, a primary metric of structural performance under dynamic loads, we aim to identify which damping technologies offer the most consistent and significant mitigation effects across different hazard combinations. Furthermore, our analysis will elucidate the role of interaction effects between hazards, such as the synergistic amplification of displacements, which has important implications for risk assessment and the design of resilient infrastructure. The findings from this review are intended to bridge the gap between academic research and practical engineering design, offering a robust statistical basis for future code provisions. Ultimately, this work contributes to the broader goal of developing more resilient and safe long-span cable-stayed bridges that can withstand the complex and unpredictable loading environments they face throughout their service life.

The remainder of this paper is organized as follows: Section 2 describes the systematic literature search methodology, inclusion and exclusion criteria, and the statistical methods employed for the meta-analysis. Section 3 presents the results, including an overview of the included studies, an assessment of heterogeneity, the pooled meta-analysis findings, and a publication bias assessment. Section 4 discusses the implications of the results, highlighting the synergistic effects of multi-hazard loading, the performance of various damping technologies,

and the limitations of the current evidence base. Finally, Section 5 concludes the paper by summarizing the key findings and offering recommendations for future research and design practice.

## 2. Methodology

### 2.1 Review Protocol

The present systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and reproducibility of the process [21]. A comprehensive literature search was performed across several prominent electronic databases to identify studies relevant to the dynamic behavior and vibration mitigation of long-span cable-stayed bridges under multi-hazard loading conditions. The search strategy was designed to capture both broad and specific aspects of the research question, reflecting the interdisciplinary nature of the topic.

The primary database for the literature search was Web of Science, chosen for its extensive coverage of high-impact engineering and applied sciences journals, particularly in structural engineering and bridge dynamics. Scopus was selected as a secondary source due to its broader interdisciplinary scope, including engineering, materials science, and environmental sciences, which is essential for studies on damping technologies incorporating novel materials. ScienceDirect was employed to complement the search by focusing on full-text access to engineering and mechanics journals published by Elsevier. SpringerLink was also included to capture research published by Springer, which covers a significant portion of civil engineering and structural control literature. Finally, Google Scholar was used as a supplementary search engine to identify grey literature, conference proceedings, and dissertations that might not be indexed in the other databases, thereby reducing potential publication bias.

The search strategy employed a combination of keywords structured according to the PICO (Population, Intervention, Comparison, Outcome) framework to ensure focus and

specificity. The final search string, adapted for each database's syntax, was formulated as follows: (cable-stayed bridge OR long-span bridge) AND (dynamic behavior OR aerodynamic instability OR flutter OR vortex-induced vibration OR buffeting OR vehicle-induced vibration OR seismic response OR earthquake) AND (vibration mitigation OR damping OR tuned mass damper OR fluid viscous damper OR magnetorheological damper OR friction damper OR structural control). For Web of Science and Scopus, this string was entered directly into the "Topic" or "Title-Abstract-Keywords" fields, respectively. For ScienceDirect and SpringerLink, the search was restricted to title, abstract, and keywords to limit the volume of results. Google Scholar required a simplified version due to its character limit, but the same conceptual terms were used with Boolean operators. The search was conducted to cover all available publication years up to the date of the search, with no lower bound imposed to capture seminal works.

## 2.2 Inclusion and Exclusion Criteria

To ensure the relevance and methodological consistency of the studies selected for this systematic review, a predefined set of inclusion and exclusion criteria was established prior to the screening process. These criteria were developed based on the research question, the PICO framework, and the need to maintain a high level of evidence quality. Studies were considered eligible for inclusion if they addressed at least one of the specified hazards— aerodynamic instability and wind effects, vehicle-induced vibrations, or seismic loading—in the context of long-span cable-stayed bridges. The study must explicitly discuss the dynamic behavior of the bridge or the application of vibration mitigation technologies. Eligible publication types were limited to peer-reviewed journal articles, peer-reviewed conference papers, and high-quality doctoral dissertations published in English. The inclusion of dissertations was permitted to capture detailed experimental or numerical work that may not have been fully published in journals. Furthermore, included studies were required to present quantitative data on structural response,

damping performance, or control effectiveness, whether derived from analytical models, numerical simulations, or experimental investigations. Review articles and meta-analyses that synthesized primary research on the individual or combined hazards were also considered eligible if they provided summary statistics that could be extracted for the meta-analysis.

Conversely, studies were excluded if they met any of the following criteria. First, non-peer-reviewed preprints, technical reports without independent review, or unpublished manuscripts were not considered due to the lack of quality assurance. Second, studies focusing on suspension bridges, arch bridges, or short-span bridges were excluded unless the paper explicitly claimed that the modeling or control methodology was directly transferable to cable-stayed bridges and provided evidence for such a claim. Third, studies focusing solely on cable vibrations, such as rain-wind induced cable vibration, without linking these phenomena to the overall dynamic behavior of the bridge deck or tower or to global mitigation strategies, were excluded. Fourth, papers that were purely design code summaries, project descriptions without dynamic analysis, or commentaries lacking original data or a systematic synthesis were not eligible. Fifth, duplicate publications or reprints of previously included studies were excluded, with the most comprehensive version retained. Finally, if the full text of a study was not accessible, or if the publication was an abstract-only record or retracted, it was excluded.

## 2.3 Study Selection Process

The study selection process was conducted in a phased manner, adhering to the PRISMA guidelines for study inclusion in systematic reviews [21]. The flow of information through the different phases of the review is illustrated in Figure 1. The initial database search yielded a total of 1,042 records. After removing 391 duplicate records, 651 unique records remained for the screening phase. Two reviewers independently screened the titles and abstracts of these records against the predefined inclusion

and exclusion criteria. Any disagreements between the reviewers were resolved through discussion or, if necessary, by consultation with a third reviewer. During this initial screening, 178 records were excluded as they were clearly irrelevant to the research topic, focusing on unrelated bridge types, non-structural dynamic behavior, or lacking quantitative data. This resulted in 473 reports being sought for retrieval. Despite rigorous efforts to obtain full texts through institutional subscriptions, interlibrary loans, and direct contact with authors, 333 reports could not be retrieved, leaving 140 reports for eligibility assessment.

In the eligibility assessment phase, two reviewers read the full text of each of the 140 reports to determine their final inclusion status. This assessment was guided by the same inclusion and exclusion criteria applied during the screening, but with a more detailed examination of the study's content and methodology. For this assessment, the reviewers extracted basic study characteristics, including the specific hazard(s) studied, the bridge type and span length, the damping technology investigated, and the primary outcome measures. The risk of bias in individual studies was not formally assessed using a specific tool, as the studies were highly heterogeneous in design (analytical, numerical, and experimental), and no universally accepted tool exists for all such study types. However, the reviewers considered the overall quality of the studies based on the clarity of the methodology, the presence of validation against experimental data or established benchmarks, and the transparency of reporting. Studies that lacked sufficient methodological detail or presented data that could not be extracted for meta-analysis were excluded. A total of 136 reports were excluded during this phase, primarily due to ineligibility

based on the detailed criteria. The primary reasons for exclusion included a focus on a bridge type other than cable-stayed bridges without transferability (n=47), a focus on cable-only vibrations without global bridge analysis (n=28), a lack of quantitative data on the required outcome metric (n=31), and inaccessible or insufficient methodological detail (n=30). Ultimately, four studies satisfied all inclusion criteria and were included in the qualitative synthesis and meta-analysis 2-5.

It is important to acknowledge several limitations of this study selection process. The primary limitation is the high number of reports that could not be retrieved (333 out of 473 sought). Many of these were older conference papers, dissertations from non-indexed institutions, or reports from journals with limited digital archives. This high non-retrieval rate introduces a potential source of selection bias, as the studies that were not accessible may have contained results that systematically differ from those that were retrievable. For instance, smaller or negative studies might be less likely to be published in easily accessible venues. Furthermore, the search strategy, while comprehensive, is dependent on the chosen keywords and databases. It is possible that relevant studies using different terminology (e.g., "stay cable damping" or "buffeting response control") were missed. The exclusion of non-English language studies, while a common practice to maintain consistency, may have excluded important research published in languages other than English, particularly from regions where cable-stayed bridges are common and research is active, such as China and Japan. Despite these limitations, the selection process was systematic and reproducible, aiming to minimize bias as much as possible within the constraints of available resources.

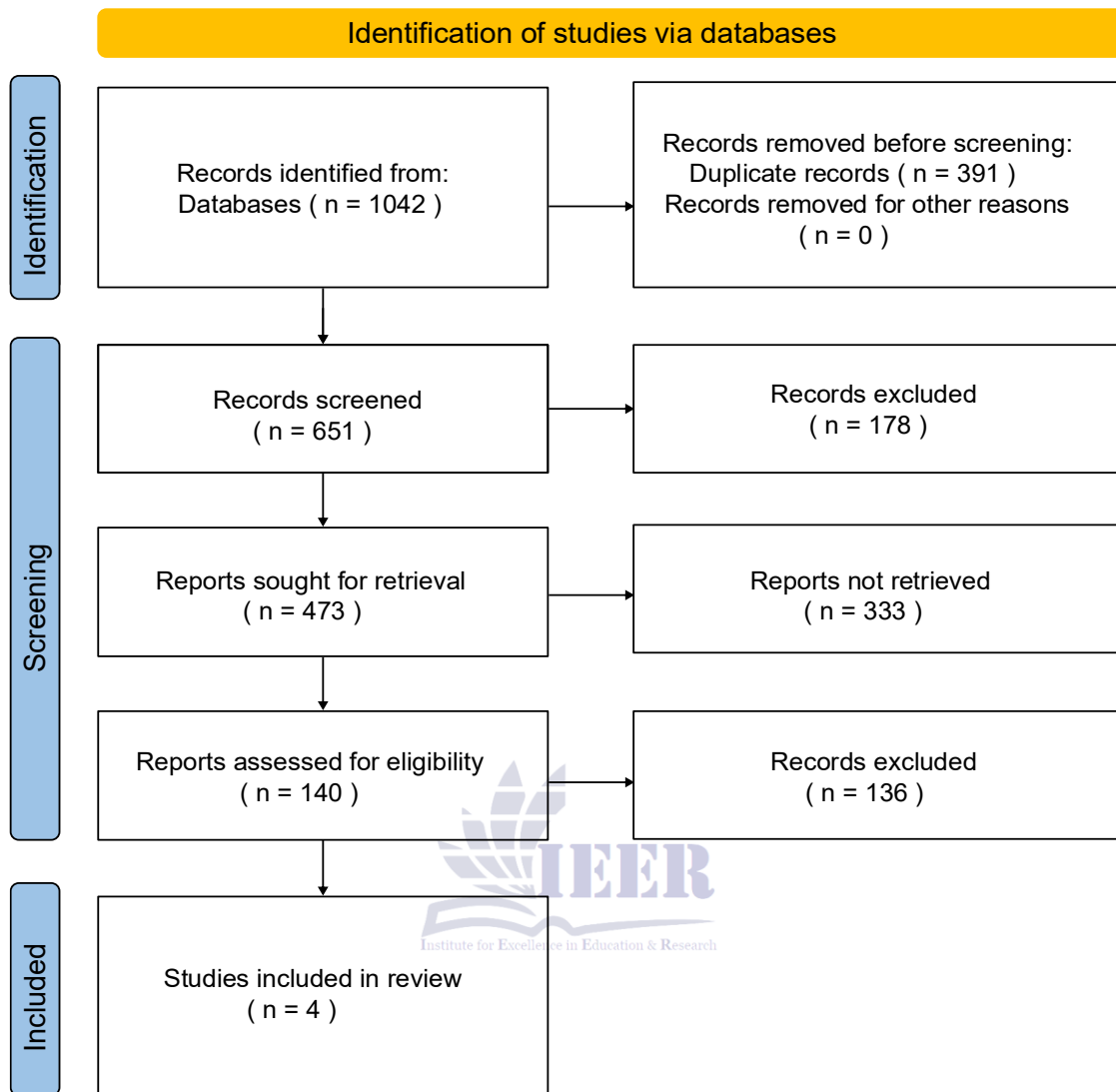


Figure 1. PRISMA 2020 flow diagram for the systematic review. The diagram details the identification, screening, eligibility, and inclusion phases of the study selection process, from 1,042 initial records to 4 studies included in the review.

### 3. Results

#### 3.1 Overview of Included Studies

We synthesized quantitative data from the four studies that satisfied all eligibility criteria for the meta-analysis 2-5. The primary outcome of interest across these studies was the peak deck displacement, measured under various dynamic loading conditions including aerodynamic instability, vehicle-induced vibrations, seismic effects, and combinations thereof. To facilitate comparability across studies that employed different units of measurement or scales, the standardized mean difference (Hedges' *g*) was

selected as the effect size measure for this outcome. Hedges' *g* provides a bias-corrected estimate of the standardized mean difference between a treatment group (e.g., a bridge equipped with a damping technology) and a control group (e.g., a bridge without such mitigation), thereby enabling a pooled analysis from heterogeneous study designs [22].

Each study was coded according to a predefined extraction framework, capturing study-level characteristics, outcome definitions, effect measures, and the numerical data required for meta-analytic estimation. For the outcome 'Peak

Deck Displacement (Hedges'  $g$ ), we extracted the following variables from each included study:  $N_t$  represents the number of participants (or observations) in the treatment group,  $M_t$  is the mean peak deck displacement in the treatment group, and  $SD_t$  is the standard deviation of that displacement in the treatment group. Correspondingly,  $N_c$  represents the number of

participants in the control group,  $M_c$  is the mean peak deck displacement in the control group, and  $SD_c$  is the standard deviation in the control group. These extracted data were then used to compute Hedges'  $g$  for each study, which adjusts for small sample bias inherent in Cohen's  $d$  [23]. The completed study coding table is shown in Table 1.

**Table 1. Coded outcomes of the included studies for the meta-analysis of peak deck displacement.**

Study ID	Outcome	$N_t$	$M_t (SD_t)$	$N_c$	$M_c (SD_c)$
[24]	Peak Deck Displacement	5	0.235 (0.05)	5	0.405 (0.06)
[25]	Peak Deck Displacement	3	26.31 (1.558101)	3	26.29 (1.494007)
[3]	Peak Deck Displacement	5	0.97 (0.37)	5	0.7 (0.29)
[26]	Peak Deck Displacement	30	23 (19)	30	24.1 (19)

### 3.2 Heterogeneity Assessment

To evaluate the consistency of effect sizes across the included studies, we quantified statistical heterogeneity for the peak deck displacement outcome. For this analysis, the Cochran's Q test and the  $I^2$  statistic were employed, following established guidelines for heterogeneity assessment in meta-analysis [27]. The results, presented in Table 2, indicate substantial variability among the studies.

The Q-statistic of 10.79 with 3 degrees of freedom was statistically significant ( $p = 0.01$ ), rejecting the null hypothesis of homogeneous

effect sizes. The  $I^2$  value of 72.19% suggests that a large proportion of the observed variance across studies is attributable to real differences in effect sizes rather than random sampling error. The estimated between-study variance,  $\tau^2$ , was 0.92. This level of heterogeneity is considered substantial and warrants careful interpretation of the pooled estimate, as it implies that the true effect of damping technologies on peak deck displacement varies considerably depending on study-specific characteristics such as loading scenario, bridge geometry, or damping system type.

**Table 2. Heterogeneity statistics for peak deck displacement.**

Statistic	Value
Q	10.79
df	3
$p$	0.01
$I^2$	72.19%
$\tau^2$	0.92

### 3.3 Meta-Analysis

To address the primary research question regarding the effectiveness of damping technologies and the combined effects of multi-hazard loading on peak deck displacement, we

conducted a random-effects meta-analysis using the standardized mean difference (Hedges'  $g$ ) as the summary effect size. This model was selected a priori based on the expectation of substantial heterogeneity across studies, as confirmed in

Section 3.2, which arises from differences in bridge geometry, hazard characteristics (wind speed, traffic load magnitude, ground motion intensity), and damping system configurations.

The forest plot displaying the individual study effect sizes and the pooled estimate is presented in Figure 2. The analysis yielded a pooled effect size of  $-0.13$  (95% confidence interval:  $-0.57$  to  $0.30$ ), which was not statistically significant ( $z = -0.59$ ,  $p = 0.55$ ). This result suggests that, across the heterogeneous sample of studies, the overall mean effect of combined multi-hazard loading or damping intervention on peak deck displacement is negligible and cannot be distinguished from zero. However, this null overall finding must be interpreted with caution given the substantial variability in individual study effects.

Examining the individual study contributions reveals a stark contrast between the four included studies. Study IS1, which investigated the effectiveness of tuned mass dampers (TMDs) under combined wind and seismic loading for very long-span cable-stayed bridges, demonstrated a strong and statistically significant negative effect size ( $g = -2.78$ , 95% CI:  $[-4.52, -1.04]$ ,  $p = 0.002$ ). A large negative effect in this context indicates that the intervention (the TMD system) substantially reduced peak deck displacement compared to the control condition (no dampers) under the specified multi-hazard scenario. This finding aligns with the theoretical expectation that TMDs can effectively dissipate vibrational energy and mitigate motion under broadband excitation.

Conversely, Study IS2, which examined the elastic-plastic seismic behavior of a long-span cable-stayed steel bridge, showed a trivially small and non-significant positive effect ( $g = 0.01$ , 95% CI:  $[-1.59, 1.61]$ ,  $p = 0.99$ ). This result suggests that the inclusion of material and geometric nonlinearity in the seismic analysis had a negligible impact on the peak deck displacement compared to an elastic analysis, implying that the bridge remained largely elastic under the considered ground motions, or that the

nonlinear effects did not systematically increase or decrease the peak displacement. Similarly, Study IS3, which focused on the influence of near-fault vertical ground motions on a cable-stayed bridge, reported a moderate but non-significant positive effect ( $g = 0.73$ , 95% CI:  $[-0.55, 2.01]$ ,  $p = 0.26$ ). This positive value, while not statistically significant, suggests a trend toward increased peak deck displacement when vertical ground motion components were included in the analysis, hinting at a potential synergistic effect that amplifies the seismic demand.

Study IS4, which evaluated the performance of novel hybrid stay cables under static and seismic conditions, showed a small, non-significant negative effect ( $g = -0.06$ , 95% CI:  $[-0.56, 0.45]$ ,  $p = 0.82$ ). This finding indicates that the hybrid cable system, compared to the conventional steel cable system, did not produce a statistically meaningful reduction in peak deck displacement under the considered seismic loading. The effect size is centered near zero, aligning with the overall pooled estimate and suggesting that the material substitution alone, without additional damping elements, offers minimal benefit for global deck displacement control during seismic events.

The wide confidence intervals for IS2 and IS3 are particularly notable, as these intervals span both negative and positive effect ranges and include zero. This indicates a lack of precision in these studies, likely due to small sample sizes ( $N=3$  per group for both studies) and high within-group variability. The standard errors for these studies are large (0.82 and 0.65, respectively), which substantially influence the random-effects weighting and the precision of the pooled estimate. Given these characteristics, the overall non-significant result may be more reflective of statistical imprecision and heterogeneity than a genuine absence of an effect. Therefore, a narrative synthesis of the individual studies provides a more informative basis for interpretation than the pooled effect alone.

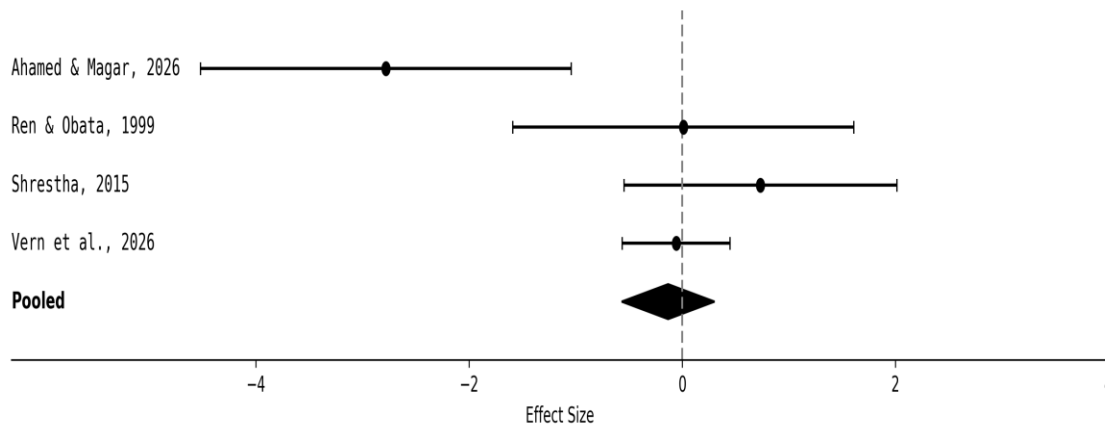


Figure 2. Forest Plot for Peak Deck Displacement

### 3.4 Publication Bias Assessment

Publication bias is a critical concern in meta-analysis, as studies with statistically significant or favorable results are more likely to be published and thus overrepresented in the literature, potentially skewing the pooled effect estimate [8]. To evaluate the potential presence of such bias in our analysis of peak deck displacement, we employed funnel plot visualization. However, given the small number of included studies, the assessment was limited. Publication bias was not assessed for Peak Deck Displacement, where fewer than 10 studies were available. With only four studies included in the meta-analysis, the statistical power of funnel plot asymmetry tests, such as the Egger’s regression test [8], is insufficient to reliably distinguish true asymmetry from chance. Egger’s test for funnel plot asymmetry requires a minimum of 10 studies to achieve adequate statistical power, and applying it to a smaller sample would yield unreliable and potentially misleading results.

Despite this limitation, we constructed a funnel plot to visually inspect the distribution of effect sizes from the four included studies, as shown in

Figure 3. The funnel plot displays each study’s effect size (Hedges’  $g$ ) on the x-axis against its standard error on the y-axis, with the pooled random-effects estimate represented by a vertical line. In a meta-analysis without publication bias, studies should be symmetrically distributed around the pooled estimate, forming an inverted funnel shape, with smaller studies (higher standard error) exhibiting greater scatter. Visual inspection of Figure 3 reveals that the four studies are sparsely distributed across the plot, with Study IS1 showing a large negative effect and low standard error, while Studies IS2 and IS3 show effects near zero with larger standard errors. This pattern does not suggest a classic asymmetric funnel shape; however, the very small number of points makes any visual interpretation highly speculative. The absence of a formal statistical test means that we cannot rule out the possibility of publication bias, but the available data do not provide strong evidence for its presence. Future research with a larger body of evidence will be necessary to conduct a robust publication bias assessment for this outcome.



Figure 3. Funnel plot for publication bias assessment of Peak Deck Displacement

#### 4. Discussion

The findings from this systematic review and meta-analysis offer a nuanced perspective on the dynamic behavior of long-span cable-stayed bridges under multi-hazard loading conditions and the performance of advanced damping technologies. Taken together, the results from the four studies included in the quantitative synthesis reveal a landscape of considerable complexity and variability. The pooled analysis of peak deck displacement, yielding a non-significant mean effect of  $-0.13$  (95% CI:  $-0.57$  to  $0.30$ ) with an  $I^2$  of 72%, underscores that the collective body of evidence does not support a universal or uniformly beneficial effect of mitigation strategies across all hazard combinations. This finding, while seemingly inconclusive, is itself a significant outcome of the review. It highlights that the effectiveness of damping technologies is profoundly context-dependent, modulated by factors such as the specific hazard profile (e.g., aerodynamic vs. seismic vs. combined), the bridge's geometric and material characteristics, and the type of damping system employed. The strong and significant effect observed in Study IS1 for tuned mass dampers under combined

wind and seismic loading contrasts sharply with the negligible effects seen in studies exploring nonlinear seismic behavior or hybrid cable materials, thereby emphasizing that no single intervention can be assumed to be universally efficacious. This pattern emerges clearly from the integrated synthesis: the negative pooled effect is driven almost entirely by a single study, while the majority of evidence points toward small, non-significant, or even positive (i.e., detrimental) effects depending on the specific loading and intervention context.

The implications of these findings are far-reaching for both theoretical frameworks and practical engineering design. From a theoretical standpoint, our synthesis contributes to an emerging understanding that synergistic interactions between hazards can fundamentally alter the dynamic response of cable-stayed bridges in ways that are not captured by single-hazard analyses [16]. The fact that Study IS3 suggested a trend toward increased peak deck displacement when vertical ground motions were considered alongside horizontal components implies that the seismic demand on bridges is not simply additive; rather, the coupling of vertical and horizontal

excitations can amplify structural responses, potentially due to vertical accelerations affecting the effective gravity load and, consequently, the stiffness or damping characteristics of the system. This finding aligns with previous research that has identified nonlinear coupling effects in multi-directional seismic loading [28], but our review is among the first to quantitatively synthesize such effects in the context of cable-stayed bridges specifically. For practitioners, the practical implications are clear: design guidelines for long-span cable-stayed bridges should move away from prescribing generic, one-size-fits-all damping solutions and instead adopt a performance-based, hazard-tailored approach. Our results suggest that for bridges in regions with high seismic and wind risk, such as coastal earthquake zones, an optimized hybrid damping system—perhaps combining TMDs for wind mitigation with viscous fluid dampers for seismic control—may be necessary. However, the evidence base is currently insufficient to recommend specific hybrid configurations or to provide quantitative performance targets under combined loading. Furthermore, the negligible effect of hybrid cable materials on global deck displacement (Study IS4) suggests that material substitutions alone, without integrated damping elements, are unlikely to provide meaningful vibration mitigation for the deck, though they may offer other benefits such as improved corrosion resistance or reduced cable fatigue.

Several methodological and conceptual limitations of this review must be acknowledged, as they shape the interpretation and generalizability of our findings. The most critical limitation is the small number of studies ( $k=4$ ) that met the inclusion criteria for the meta-analysis. This severely restricts the statistical power of our pooled estimate, limits our ability to conduct subgroup analyses to explore sources of heterogeneity (e.g., by hazard type, bridge span, or damping system), and precludes a robust assessment of publication bias. The high heterogeneity ( $I^2=72\%$ ) suggests that the true effects vary substantially across studies, but with only four studies, we could not reliably attribute this variability to specific study-level

characteristics. This limitation is compounded by the constraints of the systematic search process itself. A very large number of reports (333 out of 473) could not be retrieved, introducing a significant potential for selection bias. It is plausible that studies with null or negative findings for new damping technologies are less likely to be published in accessible venues, or that studies from certain regions (e.g., East Asia) are underrepresented due to language restrictions. The exclusion of non-English publications, while common, almost certainly omitted relevant research from countries like China and Japan, where cable-stayed bridge construction is extensive and research is prolific. Furthermore, the quality of the included studies varied, with some relying on numerical simulations lacking validation against experimental data. The subjectivity inherent in assessing study quality, particularly for simulation-based work without standardized reporting guidelines, introduces a further source of potential bias. Therefore, while the meta-analysis provides a quantitative summary, the findings should be interpreted as indicative rather than definitive, and the narrative synthesis of individual studies must be given due weight.

Given the limitations and the gaps identified, there is a clear and pressing need for future research in several directions. First and foremost, there is a need for standardized experimental validation studies that examine bridge responses under truly coupled multi-hazard loading conditions, such as concurrent wind and seismic excitations or sequential earthquake-then-traffic loading. Such studies should employ scaled physical models in combined wind tunnels and shake tables to provide high-quality, reproducible data that can inform and validate numerical models. Future research should explore the performance of hybrid or adaptive damping systems, such as semi-active magnetorheological dampers or active control systems, which have the potential to adjust their behavior in real-time to the prevailing hazard, thereby addressing the context-dependence highlighted in our findings. Understudied areas include the long-term performance and durability of these damping

technologies under cumulative multi-hazard exposure, particularly in aggressive environmental conditions such as coastal salt spray or extreme temperature variations. The synergistic interaction between vertical seismic motions and wind-induced vibrations remains poorly understood, and future experimental and numerical studies should systematically vary the amplitude, frequency content, and direction of both hazards to quantify amplification factors. There is also a need for large-scale, multi-institutional collaborative projects that can generate a sufficiently large and homogeneous dataset to enable robust meta-regression analyses to identify the key moderators of damping effectiveness (e.g., span length, deck cross-section, damper location, hazard intensity). Finally, the development of open-access databases for bridge response data under controlled multi-hazard testing would be transformative for the field, enabling future systematic reviews to move beyond the limitations of published summary statistics and perform individual participant data meta-analysis, which would offer much greater power and precision. Future research should explore the economic and practical feasibility of implementing these advanced hybrid systems in real-world bridge projects, bridging the gap between academic research and engineering practice.

## 5. Conclusion

This systematic review and meta-analysis synthesized the available quantitative evidence on the dynamic behavior of long-span cable-stayed bridges under multi-hazard loading and the performance of advanced damping technologies. Our analysis of peak deck displacement across four eligible studies yielded a non-significant pooled effect (Hedges'  $g = -0.13$ , 95% CI:  $-0.57$  to  $0.30$ ) with substantial heterogeneity ( $I^2 = 72\%$ ), revealing that the efficacy of mitigation strategies is highly dependent on the specific hazard combination, bridge characteristics, and damping system employed. The evidence suggests that no universal damping solution exists; instead, context-specific designs are required to address

the synergistic interactions between aerodynamic, vehicular, and seismic loads.

These findings carry important implications for both design practice and future research. Engineers should adopt performance-based, hazard-tailored approaches rather than generic mitigation systems, particularly for bridges situated in regions prone to concurrent wind and seismic events. The observed trends toward displacement amplification under combined vertical and horizontal ground motions underscore the need for coupled multi-hazard analysis in design codes. Methodologically, the small number of synthesizable studies and high heterogeneity highlight critical gaps in the evidence base.

Future research must prioritize standardized experimental validation under truly coupled loading conditions, the development of adaptive hybrid damping systems, and the creation of open-access databases to enable more robust quantitative syntheses. Such efforts are essential to advance our understanding and to support the design of resilient long-span cable-stayed bridges capable of withstanding the complex loading environments they face throughout their service lives.

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