Seismic Performance of RC Bridges under Near and Far Field Ground Motions in Mainshock–Aftershock Sequences: A Review

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***Abstract*—This review delves into the multifaceted aspects of the seismic performance of reinforced concrete (RC) bridges, encompassing fragility assessment, drift-based damage evaluation, and the complex effects of mainshock-aftershock (MS-AS) sequences. By examining a wide range of methodologies, including experimental studies, analytical models, and comparative analyses, this paper provides a comprehensive overview of current research trends and advancements in the field. The exploration of nonlinear modeling techniques, time-dependent degradation factors, and the integration of advanced materials offer valuable insights into evolving approaches for enhancing bridge resilience in seismically active regions. Furthermore, the paper's emphasis on identifying research gaps serves as a crucial roadmap for future investigations into the seismic performance of RC bridges. By highlighting areas that require further exploration, such as the refinement of fragility assessment methods, development of more accurate damage evaluation criteria, and improvement of modeling techniques for MS-AS sequences, this review contributes to on-going efforts to enhance the safety and durability of bridge structures. This comprehensive analysis not only consolidates existing knowledge but also paves the way for innovative research directions that could potentially revolutionize the design and assessment of RC bridges in earthquake-prone regions.**

***Index Terms*—Seismic performance, Reinforced concrete (RC) bridges, Mainshock–aftershock sequences, Fragility curves**

I. INTRODUCTION

The seismic resilience of reinforced concrete (RC) bridges has become a critical focus in earthquake engineering, driven by the increasing frequency and intensity of seismic events [1]. The vulnerability of these essential infrastructure components to mainshock-aftershock (MS-AS) sequences has prompted a shift in design philosophy [2]. Traditional force-based approaches are being replaced by more nuanced displacement- and drift-based methodologies, which offer a more accurate representation of structural damage and post-event functionality [3]. These newer approaches allow engineers to better predict and mitigate the cumulative effects of repeated seismic loadings on RC bridges, addressing the complex dynamic responses observed during MS-AS sequences [4]. Recent advancements in experimental studies, analytical modeling techniques, and comparative frameworks have significantly enhanced our understanding of the behavior of RC bridges under seismic conditions. Researchers have developed sophisticated drift limit criteria that account for the unique characteristics of different bridge components and their interactions [5]. Fragility curve evolution models now incorporate the degradation of structural capacity over multiple seismic events, providing a more realistic assessment of bridge vulnerability during an earthquake sequence [6]. Additionally, the study of MS-AS interaction effects has revealed important insights into the amplification of damage and the potential for disproportionate collapse in structures that may have appeared to withstand the initial mainshock [7]. These developments are crucial for improving the design, assessment, and retrofit strategies for RC bridges, ultimately enhancing the resilience of transportation networks in seismically active areas [8].

II. LITERATURE REVIEW

A. Experimental Studies

Shake table experiments offer essential understanding of how structures behave when subjected to seismic forces [9]. Researchers observed that longitudinal reinforcement bars began to buckle and fracture at drift ratios between 5.5% and 7.9% under peak ground accelerations of 2.0 g, highlighting the critical thresholds for structural integrity [9]. Self-centering systems, as investigated by [10], have shown promise in controlling residual drifts of up to 2.45%, offering potential improvements in post-earthquake recovery [10]. The integration of structural health monitoring technologies, such as piezoceric sensors, has opened avenues for real-time damage assessments, enabling more rapid and informed response strategies [11]. Recent advancements in seismic analysis techniques have revealed complex structural behaviours under various loading conditions. Researchers introduced the double incremental dynamic analysis (D-IDA) approach, uncovering the dual nature of masonry infills in seismic performance [4]. Although initially protective, these infills may compromise structural integrity under mainshock-aftershock (MS-AS) sequences. [12] Demonstrated the effectiveness of fiber-reinforced polymer (FRP) retrofitting in enhancing the collapse capacity of damaged piers subjected to seismic loads. [13] Quantified aftershock influence ratios (AIRs) through shake table experiments, emphasizing increased vulnerability following mainshocks. Near-fault motions, characterized by directivity pulses and vertical excitation, have been shown to impose more severe demands than far-fault motions. [14] [15] reported substantial residual drifts and end-span uplift under these conditions, whereas [16] highlighted the increased displacement ductility demands, underscoring the need for specialized seismic design considerations in near-fault regions.

B. Analytical Modelling Approaches

Drift-based fragility models have become a fundamental tool in seismic risk assessment, providing crucial insights into structural performance under earthquake loads. These models have evolved significantly over time, incorporating various advancements to improve their accuracy and applicability in different fields of study. [17] Made a notable contribution by proposing probabilistic drift limits for performance categorization, thereby enhancing the reliability of risk assessments. As infrastructure ages, the consideration of time-dependent factors is becoming increasingly important. In this context, [5] developed fragility models that incorporated corrosion effects, addressing the critical issue of deterioration of structural capacity over time.

Significant improvements in computational efficiency and modeling techniques have also been observed. Artificial Neural Network (ANN)-based methods and Incremental Dynamic Analysis (IDA)-based approaches, as explored by [18] and [8] , have streamlined the fragility analysis process. Recent advancements include the frameworks developed by [6], which employed Bayesian updating and copula techniques to assess joint seismic intensities, providing a more comprehensive understanding of seismic risks. The impact of sequential seismic events on structural integrity has been highlighted in studies such as those conducted by [19] and [3] , which demonstrated reduced drift capacity following main shocks, emphasizing the increased collapse risks in aftershock scenarios. Furthermore, the integration of advanced material models, such as fiber models incorporating flexure-shear interaction and plastic hinge behavior [20] and [21] , and the use of innovative materials such as Engineered Cementitious Composites (ECC) [7] have shown promise in improving seismic predictions and reducing structural fragility over time.

C. Comparative Studies

Near-field ground motions, characterized by concentrated energy, impose higher drift demands on structures than far-field motions, as highlighted by [22]. Although far-field effects are generally milder, they contribute to the cumulative degradation of structures over time [23]. Life-cycle assessments conducted by [1] and [2] revealed that mainshock-aftershock (MS-AS) sequences have a more significant impact on structural reliability than single events. This is further evidenced by the leftward shift of the fragility curves under sequential seismic events, as observed by [4]. The accuracy of fragility predictions is influenced by various factors, including ground motion variability, structural aging, and code provisions [24] [25]. [26] Identified spectral acceleration and displacement as optimal measures for assessing structural performance. In the case of pulse-like near-fault events, the use of spectral shape vectors reduces demand uncertainty [27]. These findings underscore the importance of considering both near- and far-field effects, as well as the cumulative impact of multiple seismic events, in the design and assessment of structures to ensure their long-term reliability and performance.

III. RESEARCH GAPS

The identified research gaps highlight critical areas requiring further investigation in bridge engineering, particularly concerning the effects of mainshock-aftershock (MS-AS) sequences on reinforced concrete (RC) bridges. One significant gap is the limited comparative data on near-field and far-field MS-AS impacts [22] [23]. This lack of information hinders a comprehensive understanding of how proximity to seismic sources influences bridge performance and damage accumulation.

Additionally, the absence of drift thresholds specifically tailored to cumulative damage in bridges presents a challenge in accurately assessing the structural integrity following seismic events[19] [3] . Another crucial area of research is the development of lifecycle-integrated performance tools that consider deterioration. Current assessment methods often fail to consider the cumulative effects of aging, environmental factors, and seismic events on bridge structures over their lifespans [5]. This gap emphasizes the need for more sophisticated modeling approaches that can predict long-term performance and guide the development of maintenance strategies. Furthermore, the limited validation of fragility models specific to MS-AS behavior in RC bridges underscores the importance of conducting extensive experimental and field studies to refine and verify the existing analytical models [6] [7] . Addressing these research gaps would significantly enhance the resilience and safety of bridge infrastructure in seismically active areas.

IV. CONCLUSIONS

This review emphasizes the critical role of drift and fragility as reliable indicators for assessing the seismic performance of reinforced concrete (RC) bridges. These parameters provide valuable insights into the structural behavior and resilience of bridges during seismic events. This study also underscores the significant impact of mainshock-aftershock (MS-AS) sequences and near-fault effects on the vulnerability of RC bridges. These complex seismic phenomena can exacerbate structural damage and compromise the overall integrity of bridge systems, highlighting the need for comprehensive analyses and design considerations. To address these challenges, this review calls for further research in two key areas. First, fragility modeling techniques must be refined to accurately capture the complex behavior of RC bridges under various seismic scenarios. This includes incorporating the effects of MS-AS sequences and near-fault ground motions into the fragility assessments. Second, the development of adaptive, performance-based seismic design frameworks is crucial for enhancing the resilience of RC bridges. These frameworks should be tailored to address evolving seismic demands and consider the dynamic nature of seismic hazards. By advancing these research areas, engineers and designers can improve the seismic performance and long-term reliability of RC bridges, ultimately enhancing the resilience of infrastructure in seismically active regions.

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