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Bibliometric Analysis on Stochastic-based Assessments of Masonry Arch Bridges

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Masonry arch bridges (MABs) remain a critical yet understudied infrastructure asset of transportation networks, particularly in terms of probabilistic assessments. This study provides a systematic bibliometric characterization of non-deterministic research on MABs, aiming to quantify the maturity and thematic composition of the field. A structured search strategy yielded 1,692 publications over more than 30 years, of which 186 employed non-deterministic approaches. An analysis of the historical evolution of research demonstrates a clear time lag relative to reinforced concrete bridges, with probabilistic studies for MABs increasing markedly only after 2014–2015. Fragility-based investigations outpace reliability analyses after 2019, while surrogate modeling applications emerge only in 2018 and remain limited. Co-occurrence networks reveal dominant clusters around seismic hazards and probabilistic modeling, with flood-related research and machine learning remaining marginal. Overall, the bibliometric results highlight a fragmented research landscape and identify key underexplored areas, including advanced surrogate modeling, multi-hazard assessment, and broader adoption of machine learning, helping to inform future research directions and knowledge transfer.

Keywords: Uncertainty quantification, reliability analysis, fragility assessment, risk assessments, reinforced concrete bridges, surrogate modeling, multi-hazard assessments.

1. Introduction

Masonry arch bridges (MABs) represent approximately 40% of the bridge stock in several European transportation networks, with most exceeding their original design life (De Santis and de Felice, 2014; Sarhosis et al., 2016; Baron et al., 2024). Many of these structures were designed using empirical rules that may be inadequate for current traffic demands, yet they are expected to remain in service with limited maintenance interventions (Niero et al., 2025). The vulnerability of this aging stock is further exacerbated by climate change–induced deterioration processes and by extreme natural hazards, as highlighted by recent collapses of historic MABs triggered by flooding and seismic actions (Buckle et al., 2012; Scozzese et al., 2019; Di Sarno et al., 2019). These events underscore the vulnerability of MABs to the inherent uncertainty of the hazards to which they are exposed and motivate a critical review of the literature on the integration of stochastic methods into MAB performance assessment. While several reviews addressing MAB behavior and assessment methods are available (Sarhosis et al., 2016; Niero et al., 2025), limited attention has been devoted to uncertainty quantification, surrogate models (SMs), and probabilistic analyses, which are well established for other bridge typologies (Samadian et al., 2025; Primo et al., 2025).

Bibliometric analysis is increasingly used to investigate research trends, influential contributions, and knowledge structures within scientific fields (Donthu et al., 2021). In the context of bridge systems, bibliometric studies have addressed structural health monitoring (Abdelkader et al., 2023), damage identification using machine learning (Ali et al., 2022), building information modeling (Li et al., 2024), digital twins (Taherkhani et al., 2024), and bridge performance under natural hazards, with emphasis on management and sustainability aspects (Santamaria-Ariza et al., 2023). While typology-specific analyses exist for reinforced concrete bridges (RCBs) (Abdelkader et al., 2023), bibliometric investigations focused on MABs remain scarce, despite their prevalence in historical and urban networks worldwide (De Santis and de Felice, 2014; Baron et al., 2024).

This study provides the first targeted bibliometric analysis of stochastic-based assessments of masonry arch bridges, integrating uncertainty quantification, fragility, reliability, sensitivity, and surrogate-model applications. By comparing MABs with reinforced concrete bridges, the paper highlights research gaps, methodological trends, and the limited adoption of machine learning and probabilistic techniques. The adopted methodology follows the framework proposed by Donthu et al. (2021), previously applied to transportation infrastructure studies with emphasis on risk, resilience, and sustainability (Santamaria-Ariza et al., 2023), and comprises research design, data compilation, construction of bibliometric networks, and analysis.

2. Research design

The present bibliometric analysis evaluates the state of the art in stochastic-based assessments of MABs, with a parallel comparison conducted for RCBs. In both cases, the system is defined as the complete bridge. Therefore, studies focusing solely on individual components were excluded. The selection of search terms is a critical step in bibliometric studies, as it strongly determines the coverage and relevance of the retrieved literature (Donthu et al., 2021; Santamaria-Ariza et al., 2023). The search strategy is structured into three hierarchical levels, summarized in Table 1.

Level 1 (n_0) targets the bridge system and excludes unrelated fields (e.g., medicine) that may use similar terminology. Level 2 (n_1–n_4) identifies literature on probabilistic assessments, addressing semantic variability in stochastic terminology. Specifically, it includes uncertainty quantification, reliability, fragility, and sensitivity analyses. Studies retrieved by any Level-2 query constitute the stochastic-based set (n_5). Level 3 (n_6–n_8) identifies works that use stochastic results to assess consequences, risk, or prioritization, including applications of surrogate models to optimize probabilistic analyses.

The search queries were applied to the Scopus bibliographic database, which offers broad coverage of publications in the field, including journal articles, conference proceedings, and books (Donthu et al., 2021; Santamaria-Ariza et al., 2023). Searches were conducted within the title, abstract, and keywords fields (TITLE-ABS-KEY), and all records up to August 2025 were considered. Figure 1 reports the number of documents retrieved for both MABs and RCBs (depicted inside a black label box). The totals were cleaned by excluding proceedings-related items, as individual conference papers were already included. The Level 1 query (n_0) indicated a substantial

Table 1. Search query combinations for masonry arch bridges excluding medical fields.

Id	Symbol	Query expression
0	n_0[1]	TITLE-ABS-KEY(”masonry arch bridge*” OR ”masonry bridge*” OR ”stone arch bridge*” OR ”arch masonry bridge*” OR ”historic arch bridge*” OR ”masonry viaduct*” OR ”stone bridge*” OR ”arched masonry bridge*” OR ”arched stone bridge*”) AND [2]
1	$n_0 \cap n_1$	n_0 AND TITLE-ABS-KEY(”failure probabilit*” OR ”reliability ind*”)
2	$n_0 \cap n_2$	n_0 AND TITLE-ABS-KEY(”fragility curve*”)
3	$n_0 \cap n_3$	n_0 AND TITLE-ABS-KEY(”sensitivity”)
4	$n_0 \cap n_4$	n_0 AND TITLE-ABS-KEY(”probabili*” OR ”stochastic” OR ”uncertain*”)
5	n_5	$n_0 \cap (n_1 \cup n_2 \cup n_3 \cup n_4)$
6	$n_5 \cap n_6$	n_5 AND TITLE-ABS-KEY(”vulnerability” OR ”risk” OR ”resilien*” OR ”robustness”)
7	$n_5 \cap n_7$	n_5 AND TITLE-ABS-KEY(”governance” OR ”manag*” OR ”decision” OR ”priorit*”)
8	$n_5 \cap n_8$	n_5 AND TITLE-ABS-KEY(”surrogate” OR ”metamodel*” OR ”machine learning”)

Notes: [1] Search terms employed for concrete bridges: TITLE-ABS-KEY(”reinforced concrete bridge*” OR ”RC bridge*” OR ”concrete bridge*” OR ”RC structure*” OR ”reinforced concrete structure*”).
[2] Scopus subject areas excluded from the search: NOT SUBJAREA(MEDI OR NURS OR VETE OR DENT OR HEAL OR BIOC OR IMMU OR NEUR OR PHAR OR CHEM).

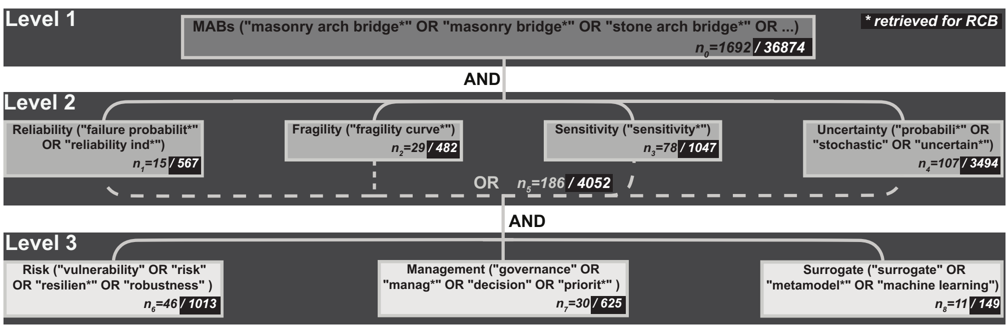

Fig. 1. Graphical representation of the different levels and search queries employed in the present bibliometric analysis. Results for RCBs are displayed inside a black label box. All articles were retrieved from the Scopus database on August 31, 2025.

disparity in research volume. Although MABs are widespread in transport networks, the corresponding literature represents only about 5% of the available for RCBs. Applying Level 2 queries greatly reduced the number of records. For MABs, the resulting counts fell below the recommended minimum for bibliometric analysis (Donthu et al., 2021). At Level 3, the smallest output corresponded to studies incorporating machine learning for structural safety for both typologies. Notably, fragility analyses yielded nearly twice as many publications as reliability-based assessments for MABs, whereas both approaches yielded similar volumes for RCBs.

3. Bibliometric co-occurrence networks

Bibliometric networks enable the visualization of scientific fields by representing nodes (e.g., publications, researchers, journals, or keywords) and edges that capture their relationships. In this study, term co-occurrence networks derived from titles, abstracts, and keywords are used to explore thematic connections and identify research gaps (Donthu et al., 2021; Santamaria-Ariza et al., 2023). Networks were constructed using VOSviewer (Van Eck and Waltman, 2010), which generates distance-based visualizations in which proximity indicates relatedness. Links between units are defined by co-occurrence frequency, and each link is associated with a strength value. Networks are clustered using the VOSviewer algorithm, facilitating the identification of research domains, thematic lines, and leading contributors. Table 2 summarizes the specifications used to construct each network. As expected, the number of links and total link strength decrease markedly from query n_0 to n_5 due to the reduced number of publications available for the latter. For the co-occurrence analysis, terms were extracted from the titles, abstracts, and keywords of publications retrieved for queries n_0 and n_5 (Figure 1). Binary counting was applied, and the minimum occurrence threshold was adjusted to obtain medium-sized networks of approximately 120 terms after excluding low-relevance terms (≈30%) (Donthu et al., 2021; Santamaria-Ariza et al., 2023). Link thickness reflects co-occurrence strength, so frequently co-occurring terms are positioned closer together.

Figure 2 presents the co-occurrence network for query n_0, focused on system identification (MABs). Terms within each cluster were analyzed to identify the research areas that best represent the cluster. The cluster link strength (CLS) can be used to measure how connected and represented a cluster is in the literature. The red cluster, structural analysis, has the highest CLS, accounting for 47% of the total link strength (TLS), and includes components, capacity analysis, and failure modes. The blue cluster, modeling and monitoring, accounts for 21% of the TLS and contains damage identification methods, e.g., NDTs, with a focus on flood hazards. The green cluster,

Table 2. VOSviewer specifications for term co-occurrence networks.

Search query	Co-occurrence (Terms) n_0	n_5
Total records	1692	186
Count type	Binary	
Unit	Terms	
Min occurrences[1]	20	23
Units	160	174
Relevant units[2]	75%	69%
Selected units	120	120
Clusters	5	5
Links	10,096	6,040
TLS	88,276	20,104

Notes: [1] Adjusted to obtain medium-size networks (∼120 terms).
[2] Percentage of units selected based on relevance score, excluding terms with low scores.

bridge engineering, emphasizes the operation, loading, and management of MABs within transportation networks. Finally, the yellow and purple clusters have the lowest CLS, each representing less than 10% of the TLS. The yellow cluster, structural dynamics, focuses on seismic hazards, while the purple cluster, heritage preservation, addresses deterioration associated with long periods of operation. Clusters are not entirely isolated, which indicates that terms can be transversal across multiple research areas. For example, the yellow and blue clusters, related to structural dynamics and numerical modeling, are closely connected due to the large body of research on various numerical modeling techniques (Tubaldi et al., 2020; Pantò et al., 2022; Farneti et al., 2024), while the blue and purple clusters share many damage detection methods commonly applied in deteriorating structures, such as historical masonry constructions.

Figure 3 presents the co-occurrence network for query n_5, focused on stochastic-based performance assessments of MABs. Similar to Figure 2, clusters structural dynamics (green) and modeling and monitoring (red) remain, while the previous structural analysis cluster is divided into structural capacity (yellow)

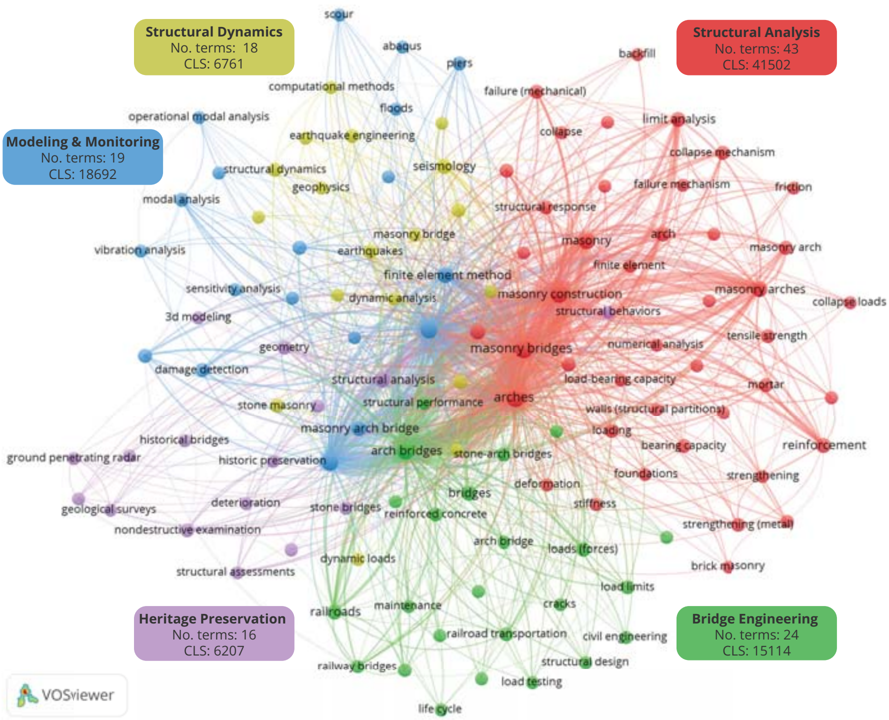

Fig. 2. Co-occurrence network for query n_0, representing the bridge system (MABs). Note: Color coding applies to the online version.

and structural failure (purple). In terms of TLS contribution, modeling and monitoring remains around 20%, structural dynamics increases to 24%, and structural analysis decreases to 38%, with the newly emerged probabilistic methods cluster (blue) accounting for 18%. Keywords associated with probabilistic assessments are located near structural clusters, highlighting their strong association with this field (Gönen and Soyöz, 2022; Bouzas et al., 2023; Baron et al., 2024; Cabanzo et al., 2025). Within the probabilistic methods cluster, the keyword Bayesian network (BN) appears as the only ML technique, mainly linked to condition-based assessments (Rafiq et al., 2015) or hazard intensity prediction (Maroni et al., 2021). The nearby term Bayesian inference, although not an ML algorithm, is relevant as a statistical framework that updates probabilities using Bayes' theorem (Moreira et al., 2017; Bouzas et al., 2023). In the green cluster (structural dynamics), fragility-related keywords reflect research focused on quantifying the effects of hazard-related aleatory uncertainties on the dynamic response of MABs (Shimpi et al., 2021; Manjily et al., 2025; Homaei and Yazdani, 2025).

4. Discussion and conclusions

Figure 4 shows the historical evolution of each query for both MABs and RCBs, highlighting a pronounced imbalance in research volume between the two typologies: by 1990 the number of RCB publications already exceeded the current total for MABs, and both typologies show a similar reduction between total publications (n_0) and probabilistic analyses (n_5). Initially, reliability (n_1) and fragility (n_2) studies followed comparable trends, but from around 2019 fragility

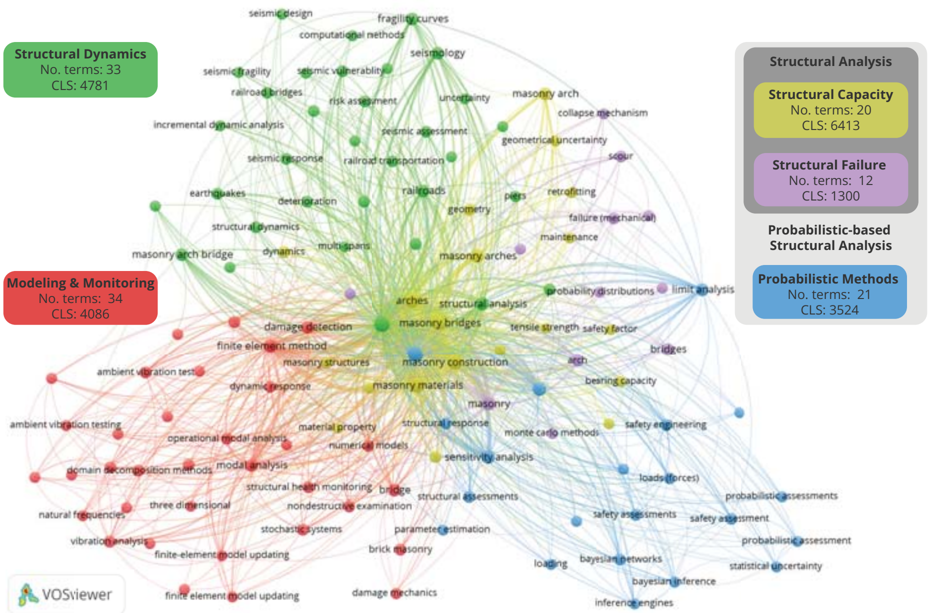

Fig. 3. Co-occurrence network for query n_5, representing stochastic-based assessments of MABs. Note: Color coding applies to the online version.

research increased markedly for MABs, nearly doubling reliability-focused studies, whereas for RCBs the two remained similar over time. Non-deterministic assessments of MABs rose around 2014–2015, and SMs began appearing in 2018, although their integration into probabilistic analyses remains limited. For RCBs, SMs appeared one year earlier and with a larger publication volume. Overall, stochastic-based structural assessments have gained attention due to the need for rapid evaluations that account for structural and hazard uncertainties, yet MAB research remains limited despite its relevance to transportation networks. A bibliometric analysis of 1,692 works since 1972 revealed an upward research trend, with UQ and sensitivity analyses representing the largest share, followed by risk and management studies, while ML applications remain scarce, consistent with their limited presence in the co-occurrence networks (Figures 2–3).

Bibliometric networks (Figures 2–3) were used to highlight potential research gaps. Most clusters at both system and probabilistic levels are highly interconnected, with many keywords appearing across multiple clusters. For instance, "modeling" dominates the literature and is mainly associated with continuous finite element models (FEM), whereas discrete element models (DEM) are absent. Seismic hazards are the most studied, followed by floods, with seismic research primarily addressing hazard-based uncertainties and scour-related studies more closely linked to structural uncertainties. This distinction is reflected in Figure 3, where seismic-fragility terms (green cluster) are positioned opposite to probabilistic-assessment terms (blue cluster). The analysis also indicates a need to transfer probabilistic-safety assessment knowledge (blue cluster) to other domains (structural dynamics and modeling and monitoring) to better address structural epistemic uncertainties. While bibliometric analysis identifies major research streams, it does not exclude the existence of literature addressing specific gaps. Thus, the study provides a broad overview of research concentration. Limita-

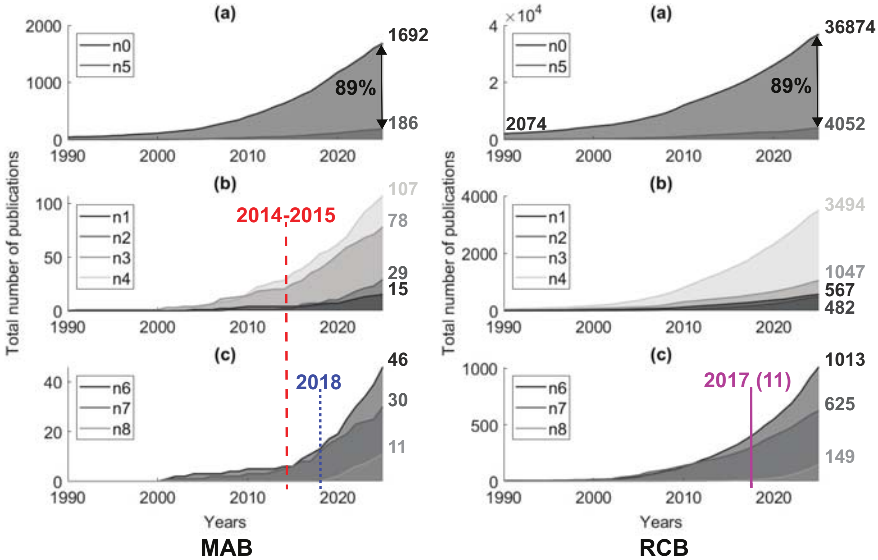

Fig. 4. Historical evolution of research on MABs and RCBs across the search queries: (a) system (n_0) vs. stochastic-based (n_5); (b) stochastic approaches (n_1–n_4); (c) applications of stochastic assessments (n_6–n_8). Dashed: increased output in levels 2–3; dotted: first surrogate models in MAB safety assessments; solid: n_8 RCB publications exceed MAB publications. Data retrieved from Scopus on 31 August 2025.

tions include search-term selection, which may have omitted contextual studies despite multiple trial iterations, and the reliance on a single database.

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