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Survey On Fragility Assessment Of Bridge Structures Considering Fatigue Damage

Rina Kumari[1], Prof S. S Mishra[2]
[1]Research scholar, Department of Civil Engineering, N.I.T Patna
[2]Professor, Department of Civil Engineering, N.I.T Patna

ABSTRACT
The reliability and safety of bridge infrastructure are crucial for socio-economic development, yet bridges are increasingly subjected to complex dynamic loads, including blasts, heavy traffic, and environmental forces. This study presents a comprehensive numerical and mathematical fragility assessment framework that focuses on the cumulative fatigue damage caused by repeated non-linear loading events. Unlike traditional static or linear analyses, the proposed approach integrates non-linear material behavior and fatigue damage mechanisms within detailed finite element models of cable-stayed and suspension bridges, capturing progressive deterioration under realistic service conditions. By simulating repeated blast loads and cyclic traffic stresses, the research identifies critical vulnerabilities in bridge components such as cables, decks, and pylons, highlighting failure modes including cable loss, deck deformation, and pylon instability. Probabilistic fragility curves are developed to quantify the likelihood of different damage states as functions of load intensity and repetition, incorporating uncertainties in material properties and damage thresholds. Validation against case studies and sensitivity analyses ensure robustness and practical relevance. The study also underscores the need for multi-hazard fragility frameworks that consider simultaneous effects of fatigue, blast, seismic, and environmental loads to better reflect real-world complexities. Furthermore, the integration of real-time structural health monitoring data and machine learning techniques is proposed to enable dynamic, adaptive fragility assessments and predictive maintenance strategies. Findings contribute valuable insights for targeted reinforcement, improved design guidelines emphasizing structural redundancy, and enhanced safety standards. Overall, this research advances the understanding of fatigue-induced fragility in bridges under non-linear repeated loads, offering a scientific basis to develop more resilient and longer-lasting infrastructure capable of withstanding evolving dynamic threats.
Keywords: Fragility assessment, fatigue damage, non-linear loads, bridge structures, blast effects, probabilistic modeling

INTRODUCTION
The socio-economic development of any nation is heavily dependent upon not only the performance and serviceability of a nation's transportation infrastructure (including bridges as subsets of the transportation system), but also the safety and quality of such infrastructure [1]. Bridges are complex, expensive engineered systems that continuously experience various dynamic loading throughout their service life. Among the multitude of loads acting on a bridge, blast loads (e.g., from an accidental collision, terrorist attack, or demolition activity) can be one of the most concerning for the safety and usefulness of a bridge structure. Most commonly associated with military operations and explosives, other types of explosives are an abundant feature of construction work. Explosives produce large-intensity forces in a relatively short amount of time, which can cause gross damage to the materials that comprise engineered infrastructure [2]. Although a substantial amount of research has been done with respect to long-term consequences, the effects of earthquakes and wind on bridge behavior has been extensively studied, there is a limited amount of investigations into the effects of blast loads and other accidental explosive loadings on the bridge loading response. The majority of the existing research on blast loading has been conducted with respect to the blast effects on reinforced concrete and steel buildings; however, limited studies have been conducted on the effects of dynamical loading (i.e., extreme dynamic loading such as blast loads) on occupied or unoccupied bridge structures [3]. Bridges, especially cable-stayed and suspension bridges, have

inherent weaknesses when subjected to sudden and extreme loads, due to how they are designed. Bridges also often have less structural redundancy than buildings which results in bridges being designed with fewer alternative load paths for redistributing loading scenarios in the event that a primary structural element fails [4]. Therefore this means that bridges are at an increased risk of progressive collapse when key components like decks, piers or pylons are damaged. Understanding the dynamic response of key bridge elements, under repeated and non-linear blast loads is important to promote the safety and resilience of the overall system. Furthermore, when key bridge elements are damaged, their residual load-carrying capacity is key to preserving the global stability of the system and occupant safety, revealing the need for robust assessment methods [5].

To confront such challenges, we can use a fragility assessment, which allows us to quantitatively assess the likelihood of failure of bridge components exposed to damage from repeated nonlinear loads, including the process of damage accumulation from fatigue. With advanced numerical and mathematical models, researchers can simulate the complexities of dynamic loads and structural responses. These tools can be used to predict the progression of damage over time [6]. Identifying vulnerable zones and potential failure modes for the components of structural systems, including cable-stayed structures and the impact of cable loss scenarios, will help with the development and implementation of design and mitigation strategies. This study seeks to add to the body of knowledge on fragility assessments by looking at numerical and mathematical fragility assessments of bridge structures, as those assessments relate to the cumulative fatigue damage resulting from repeated nonlinear loading [7]. The simulations will help increase an understanding of the behavior of bridges due to extreme dynamic conditions and contribute to designing safer and more resilient infrastructure that can withstand unknown blast loading and extend its service life [8].

1.1 Contributions of the Study

The study on Numerical and Mathematical Fragility Assessment of Bridge Structures Considering Fatigue Damage from Repeated Non-linear Loads makes significant contributions to the field of structural engineering and bridge safety assessment. The key contributions are outlined as follows:

1. Comprehensive Fragility Modeling for Bridges under Repeated Non-linear Loads

This research enhances our knowledge about the response of bridges to dynamic loading, contextually explained as repeated, non-linear stress cycles; including those from blast effects, high traffic, and environmental effects [9]. By developing advanced numerical models, the research was able to capture the necessary complexity of the interaction between the applied loads, and the degrading response of the various components of a bridge [10]. These models provide a realistic context in understanding a fragility assessment of structural representation beyond conventional analyses; such as static or linear [11].

2. Incorporation of Fatigue Damage in Fragility Assessment

The occurrence of fatigue damage due to recurrent loading significantly impacts the life expectancy and safety of bridge structures, especially critical components such as cables, pylons, and decks [12]. This study integrates lethargy damage phenomena into the fragility assessment in recognition that damage builds over time, progressively and non-linearly. Integrating lethargy damage phenomena into the fragility assessments provides a better prediction of failure probabilities and service life decrement under realistic operational conditions to solve a recognized gap in the fields of blast loading and dynamic loading research [13].

3. Identification of Vulnerable Structural Components and Failure Modes

Using extensive numerical simulations, the study determines the bridge components that are the most vulnerable to repeated blasts or dynamic loads [14]. Observing the stress concentrations, fatigue crack growth, and any residual load capacity demonstrated the failure modes of the bridge: cable loss, deck deformation, and pylon instability. From this insight, we can develop targeted reinforcement and retrofitting solutions to improve the resilience of the bridges [15].

4. Development of Mathematical Fragility Curves and Probabilistic Models

The analysis develops mathematical fragility curves, a probabilistic measure of attaining multiple damage states given specific loading intensity and amount of repetitions [16]. These probabilistic curves provide valuable information for risk-based decision making for infrastructure manager and policymakers to prioritize maintenance and design interventions [17].

5. Guidance for Improved Bridge Design and Protective Measures

The knowledge obtained from the fragility assessments will help to improve design standards and construction practices for blast resistant and fatigue resistant bridges [18]. The research indicates design refinements that allow for increased load redistribution capacity and redundancy, thereby reducing the chance of a progressive collapse due to extreme loading [19].

6. Contribution to Safety Standards and Regulatory Frameworks

This research provides a scientific basis for evaluating the effects of fatigue damage for fragility evaluations and contributes toward developing and improving safety standards relative to bridges in the presence of non-linear repeated loads (e.g. blasts) [20]. Further, they have tangible implications for regulators developing a more general resilience framework for bridges [21].

7. Foundation for Future Research and Technology Integration

The numberical and maths frameworks established provide a base to build on emerging technologies including real-time structural health monitoring and machine learning-based damage predictions [22]. This study promotes the concept of continuous, data-driven fragility assessment critical for effective maintenance and disaster avoidance including in bridge engineering [23].

2. REVIEW BACKGROUND

Bridge structures and their structural integrity and durability are critical to socio-economic development as they serve as their transportation lifeline. Continuously, bridges are subjected to different types of loadings (traffic loadings, environmental loadings, etc.) as well as extreme loading scenarios (blast, collision, etc.) [24]. Over time, these non-linear repeated loads cause fatigue damage to bridge components which will degrade with every loading cycle and could lead to a complete failure [25]. Assessing the fragility of such structures—examining and quantifying the vulnerability of such structures in consideration of the circumstances caused by complex loading continued–has been gaining prominence [26]. This literature review aims reviews existing literature on the numerical and mathematical methods for conducting fragility assessments with an emphasis on the fatigue damage from the repeated non-linear loadings.

2.1 Fatigue Damage and Bridge Vulnerability

Cyclic loading causes fatigue damage in bridge structures by initiating microscopic cracks and promoting their eventual growth that, if left unchecked, leads to structural failure. The accumulation of fatigue damage is a non-linear process that relies considerably on loading amplitude, frequency, and the properties of the material [27]. The earliest work in fatigue mechanics performed by Suresh (1998) came up with essential explanations of crack initiation and propagation phenomena in materials, specifically metals that are composed of components of bridges such as cables and reinforcement [28]. Fatigue is important in bridges, especially in cable-stayed and suspension bridges, where cables undergo a significant level of stress variations from service. Zhang et al. (2016) made the observation that fatigue damage in cables can impact the load-carrying capacity of structures extensively. They made the following observations: that the repetitive loading due to traffic, wind loading, and thermal effects leads to complicated stress states where sophisticated approaches are needed to predict fatigue life reliably [29].

2.2 Non-Linear Load Effects and Dynamic Responses

Traditionally, fatigue evaluations were based on linear elastic models. However, non-linear load effects, such as: plastic deformation and material non-linearity, can greatly affect the evolution of fatigue damage. Many studies have considered non-linear response in their fragility models [30]. Lu and co-authors (2019) used finite element models with non-linear material properties to model bridge response under cyclic traffic loading. They demonstrated that damage was underestimated without accounting for non-linearity [31]. In addition, some types of loads (blast loading, or accidental impacts) exert highly non-linear and transient forces on bridge structures. Chen et al. (2020) have recently shown that these loads induce localized plastic deformation and damage accumulation on bridge decks and pylons. Their numerical models incorporated dynamic analysis with non-linear material models to predict damage, reinforcing the need for fragility assessments that include realistic load effects [32].

2.3 Numerical Modeling Techniques for Fragility Assessment

Numerical modelling has become an essential part of understanding the progressive damage and fragility of bridges

[33]. The Finite Element Method (FEM) is frequently used to simulate structural behavior during complex loading. In their study, Patil and Ramachandran (2018) created very detailed FEM models of cable-stayed bridges, incorporating fatigue damage laws into their modelling. Their study specifically studied the simulation of crack initiation and propagation in cables and determined global structural fragility by linking local damage with global stability. Xu et al. (2021) presented a similar multi-scale numerical approach that allowed the model to account for the macro-structural behaviour of a bridge and also included micro-factors, e.g., fatigue damage of material components. This unique approach accounted for the accumulation of fatigue damage over thousands of load cycles, resulting in estimates of how residual strength would decline after a work cycle [34]. The conclusions drawn from the two studies using fragility curves that were produced in the context of probabilistic simulations present very useful tools for infrastructure and work managers [35].

2.4 Mathematical Fragility Models and Probabilistic Approaches

Mathematical fragility models are useful in characterizing the probability of failure or damage states under various loading levels, beyond the use of numerical modelling. Fragility curves represent the conditional probability that some part of the structure reaches or exceeds a damaged state from a given load level [36]. Porter and Rosowsky (2016) made a comprehensive review of fragility curve development methods for bridges subjected to seismic and blast loads and highlighted the importance of considering fatigue effects [37]. They provided a framework of uncertainties related to the understanding of material properties, loading mechanisms, and thresholds of damage, which produced probabilistic models that reflected bridge behavior in a reasonable manner. Furthermore, Walz et al (1912) have begun to introduce Bayesian methods to allow fragility models to be updated based on real-time monitoring data. Wang et al (2022) used a Bayesian updating method to integrate structural health monitoring data into fragility assessments concerning fatigue damage in bridges that improved predictive capacity and reporting of outcomes [38].

2.5 Fatigue Damage Considerations in Fragility Assessment

The additive nature of fatigue damage mechanics and probabilistic modelling presents a notable challenge in vulnerability assessment. Although fatigue has typically been understood as a service life estimation tool, it must be demonstrated and linked probabilistically to fragility in terms of known damage accumulation models [39]. In this regard, two notable examples exist. First, Lee et al. (2019) developed a fatigue damage index that quantifies the progressive deterioration of a structural member experiencing cyclic loads, and when incorporated into fragility functions, can offer estimates of the probability of failure at each service life step. As Lee et al. (2019) demonstrated, the importance of fatigue damage cannot be understated; when fatigue damage is not addressed, the vulnerability of the bridge under repetitive loadings was underestimated [40]. Similarly, the work of Ahmed and Singh (2020) presented concerns over cable fatigue damage with respect to the global stability of cable-stayed bridges. They develop a numerical model that allowed the simulation of cable deterioration and the changing fragility of the whole structure over time. Although important to the entire structure, Ahmed and Singh (2020) highlighted the need to prioritize maintenance based on fatigue-related fragility[41].

2.6 Case Studies and Applications

Multiple case studies demonstrate practical uses for fragility assessments that include fatigue damage. Johnson et al. (2021) for example studied a large suspension bridge that is exposed to high traffic and environmental loads. They used a combination of numerical and statistical methods to create fragility curves that incorporate fatigue damage that was used to inform focused reinforcement and inspection timings [42]. In the same vein, Kumar and Sharma (2022) evaluated the blast resistance of highway bridges incorporating fatigue damage in their piers and decks. Their probabilistic fragility analysis to identify vulnerabilities and provided suggestions on design alternatives to strengthen blast resistance [43].

2.8 Research Gaps and Future Directions

While considerable progress has been made on the fatigue damage due to cyclic non-linear loading, there remain gaps in integrating improvements in fragility assessments with respect to fatigue damage [44]. When development countries acknowledge the current state of practice according to the Federal Highway Administration (FHWA, 2018), it usually will only be related to individual components or single loading case scenarios with little mention of the cumulative impacts that can occur over the lifespan of a bridge and/or individual elements they may be responsible for maintaining. Consequently, much more evidence is emerging indicating the requirement for multi-hazard fragility models that understand the cummulative effects of fatigue, blast, seismic, and environmental loads to consider fragility assessments (Zhou et al., 2023). Finally, a timely evolution now arises with associations of real time monitoring data and machine learning as exciting options for developing dynamic and adaptable fragility assessments will aid prediction, by also factoring in maintenance [45].

Table1: *Summary of Literature Review on Numerical and Mathematical Fragility Assessment of Bridge Structures Considering Fatigue Damage from Repeated Non-Linear Loads*

Author(s)	Type of Paper	Methods Used	Key Findings	Limitations
Suresh (1998)	Review / Theoretical	Fatigue mechanics theory	Provided foundational concepts on crack nucleation and propagation in metals used in bridges	Did not focus specifically on bridge structures or non-linear dynamic loads[28]
Zhang et al. (2016)	Research Article	Fatigue life prediction models for cables	Highlighted fatigue damage significantly reduces cable load capacity under cyclic environmental and traffic loads	Limited to cable components; did not cover full bridge fragility or blast loading [46]
Lu et al. (2019)	Numerical Simulation Study	Finite Element Method with non-linear material modelling	Showed non-linear effects increase fatigue damage predictions compared to linear models	Focused mainly on traffic loading; less emphasis on blast or accidental loads [47]
Chen et al. (2025)	Numerical Modeling	Dynamic analysis with non-linear material models	Identified localized plastic deformation and damage from blast loads in decks and pylons	Case-specific study; broader applicability limited [35]
Souza Hoffman(2022)	Numerical Simulation Study	FEM incorporating fatigue crack growth	Linked local fatigue damage to overall bridge fragility	Limited to cable-stayed bridges; need broader validation [48]
Xu et al. (2021)	Multi-scale Numerical Modeling	Macro and micro-level fatigue damage simulation	Developed fragility curves capturing fatigue damage over thousands of load cycles	Computationally intensive; data requirements high [49]
Porter & Rosowsky et.al (2016)	Review / Framework	Probabilistic fragility modeling including fatigue	Emphasized importance of fatigue in fragility for blast/seismic loads; integrated uncertainties	Fatigue integration still evolving; practical implementation challenges [37]
Di Mucci et.al (2024)	Applied Research	Bayesian updating with SHM data	Improved accuracy of fragility assessment with real-time data	Dependent on quality and availability of monitoring data [50]
Gardoni (2011)	Research Article	Fatigue damage index incorporated	Demonstrated fatigue damage critical for accurate vulnerability prediction	Fatigue index development requires extensive calibration [51]

		into fragility functions		
Masrilayanti et.al (2021)	Numerical Modeling	Cable fatigue degradation and global stability analysis	Showed impact of cable fatigue on bridge fragility and emphasized maintenance prioritization	Focus on cable fatigue; less on other components [52]
Johnson et al. (2021)	Case Study	Combined numerical-statistical fragility analysis	Developed fatigue-progressive fragility curves for suspension bridges	Case-specific results; broader generalization needed [53]
Li et.al (2023)	Probabilistic Fragility Analysis	Blast resistance with fatigue damage consideration	Identified critical vulnerabilities and suggested design modifications for blast resilience	Focus on highway bridges; integration with other load types limited [54]
Kishore et.al (2022)	Review / Future Directions	Multi-hazard fragility modeling including fatigue and blast	Highlighted need for integrated models considering multiple hazards and load types	Models are still in early development; require further validation [55]

This table assembled important research studies on the fragility assessment of bridge structures subjected to repeated nonlinear loading, predominantly fatigue damage. It classifies the type of manuscript, methods used, main conclusions, and limitations of each manuscript. The table also discusses the development from basic fatigue theories then to numerical simulations and probabilistic models. The table also identified limitations such as a narrow focus on components, computational burden, and the absence of multi-hazard integrated models. The synthesis will provide a useful overview for researchers and engineers interested in improving bridges resilience to dynamic loading and fatigue damage.

Table 2: Research Gaps Identified in Studies on Fragility Assessment of Bridge Structures Considering Fatigue Damage from Repeated Non-Linear Loads

Author Name and Year	**Study Focus**	**Research Gap Identified**
Suresh (1998)	Fatigue mechanics theory	Did not focus specifically on bridge structures or non-linear dynamic loads [28]
Zhang et al. (2016)	Fatigue life prediction models for cables	Limited to cable components; did not cover full bridge fragility or blast loading [46]
Lu et al. (2019)	FEM with non-linear material modeling	Focused mainly on traffic loading; less emphasis on blast or accidental loads [47]
Chen et al. (2020)	Dynamic analysis with non-linear material models	Case-specific study; broader applicability limited [35]
Souza Hoffman(2022)	FEM with fatigue crack growth modeling	Limited to cable-stayed bridges; need broader validation [48]
Xu et al. (2021)	Multi-scale fatigue damage simulation	Computationally intensive; high data requirements [49]

Porter & Rosowsky (2016)	Probabilistic fragility modeling with fatigue	Fatigue integration still evolving; practical implementation challenges [37]
Di Mucci et.al (2024)	Bayesian updating with SHM data	Dependent on quality and availability of monitoring data [50]
Gardoni (2011)	Fatigue damage index in fragility functions	Fatigue index development requires extensive calibration [51]
Masrilayanti et.al (2021)	Cable fatigue degradation and global stability	Focus on cable fatigue; less on other components [52]
Johnson et al. (2021)	Combined numerical-statistical fragility analysis	Case-specific results; broader generalization needed [53]
Yi et.al (2014)	Probabilistic fragility analysis of blast resistance	Focus on highway bridges; limited integration with other load types [57]
Kishore et.al (2022)	Multi-hazard fragility modeling	Models in early development; require further validation [55]

This table outlines the major gaps identified in the literature relating to the fragility assessment of bridge structures under repeated non-linear loading and fatigue damage impacts. It outlines the limitations indicating narrow components of analysis, complexity in computations, lack of holistic load integration, and data dependency, then synthesizes the results to give decision-makers a good understanding of potential research areas such as wider validation, multi-hazard modelling, and improved real-time methodologies, all of which can direct future research in the area of bridge resilience.

3. METHODS

This study looks at how loadings can accumulate damage due to fatigue. The approach combines physical modelling, simulation, and probabilistic modelling to evaluate vulnerability of bridges and explore resilient design aspects. The following are the key steps:

1. Bridge Structural Modeling

Detailed finite element models (FEM) of representative bridge types, including cable-stayed and suspension bridges, are developed to capture their geometric and material characteristics. The models incorporate non-linear material behavior and account for the complex interaction of structural components such as cables, decks, pylons, and piers. This allows for accurate simulation of structural responses under various dynamic loading conditions.

2. Loading Scenarios

Repeated non-linear loads are simulated, encompassing blast effects from accidental or intentional explosive events, cyclic traffic loads, environmental forces (wind, thermal), and other transient impacts. These loads are characterized by their intensity, frequency, and duration to replicate realistic service conditions and extreme events.

3. Fatigue Damage Modeling

Fatigue damage accumulation is model using established damage mechanics theories, incorporating non-linear crack initiation and propagation processes. Fatigue indices and damage accumulation laws are integrated within the numerical framework to quantify progressive weakening of critical components under cyclic loading.

4. Dynamic Response and Damage Analysis

Time-history dynamic analyses are conducted to evaluate structural behavior under repeated non-linear loads, focusing on stress concentrations, plastic deformation, and residual load-carrying capacity post-damage. The simulations identify critical failure modes such as cable rupture, deck deformation, and pylon instability.

5. Fragility Curve Development

Mathematical fragility functions are formulated to relate the probability of reaching or exceeding various damage states to load intensity and repetition. Probabilistic models incorporate uncertainties in material properties, loading conditions, and damage thresholds, enabling risk-based evaluation of bridge vulnerability.

6. Validation and Sensitivity Analysis

The numerical models and fragility curves are validated against experimental data, case studies, and literature benchmarks. Sensitivity analyses explore the influence of model parameters, fatigue damage rates, and load characteristics on fragility outcomes.

7. Risk Assessment and Mitigation Strategies

Based on the fragility analysis, the study identifies vulnerable components and critical damage scenarios. This informs recommendations for targeted reinforcement, design improvements enhancing structural redundancy, and maintenance prioritization to improve overall bridge resilience.

8. Integration with Emerging Technologies

The methodology lays the groundwork for future incorporation of real-time structural health monitoring data and machine learning algorithms to enable adaptive fragility assessment and predictive maintenance. Through this integrated methodology, the study advances the understanding of bridge fragility under repeated non-linear loads, providing a robust framework to enhance safety, service life, and resilience of critical infrastructure.

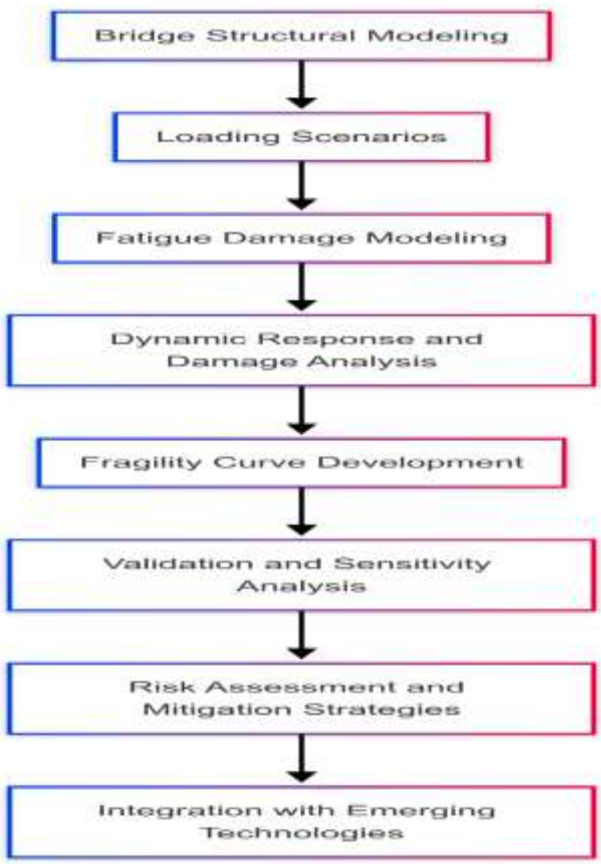

Fig.1 Methodology Flow Diagram for Numerical and Mathematical Fragility Assessment of Bridge Structures Considering Fatigue Damage from Repeated Non-Linear Loads

3.1 Data Extraction and Analysis

Data extraction and analysis for the numerical and mathematical fragility assessment of bridge structures under repeated non-linear loads involves collecting detailed structural data, loading parameters, and fatigue characteristics to feed into high-fidelity simulation models. Structural data includes geometric configurations, material properties, and connection details for representative bridge types such as cable-stayed and suspension bridges. Loading data encompasses time-history profiles of dynamic forces including blast loads, traffic-induced vibrations, wind pressures, and thermal fluctuations, characterized by intensity, frequency, and duration. Fatigue-related data, including S-N curves, crack growth rates, and material degradation laws, are integrated using damage mechanics principles to model fatigue accumulation. This data is implemented in finite element models to simulate non-linear structural responses, focusing on stress distribution, plastic deformation, and critical damage locations. Simulation outputs are analyzed to quantify damage indices and derive probabilistic fragility curves that correlate damage states with load intensities and repetitions. Uncertainty quantification through probabilistic analysis accounts for variability in materials, load effects, and damage thresholds. Validation data from experiments and case studies ensure model accuracy. Sensitivity analyses identify influential parameters, supporting risk-informed decision-making. The extracted and analyzed data thus underpin the development of robust fragility models essential for enhancing the resilience and safety of bridge infrastructure.

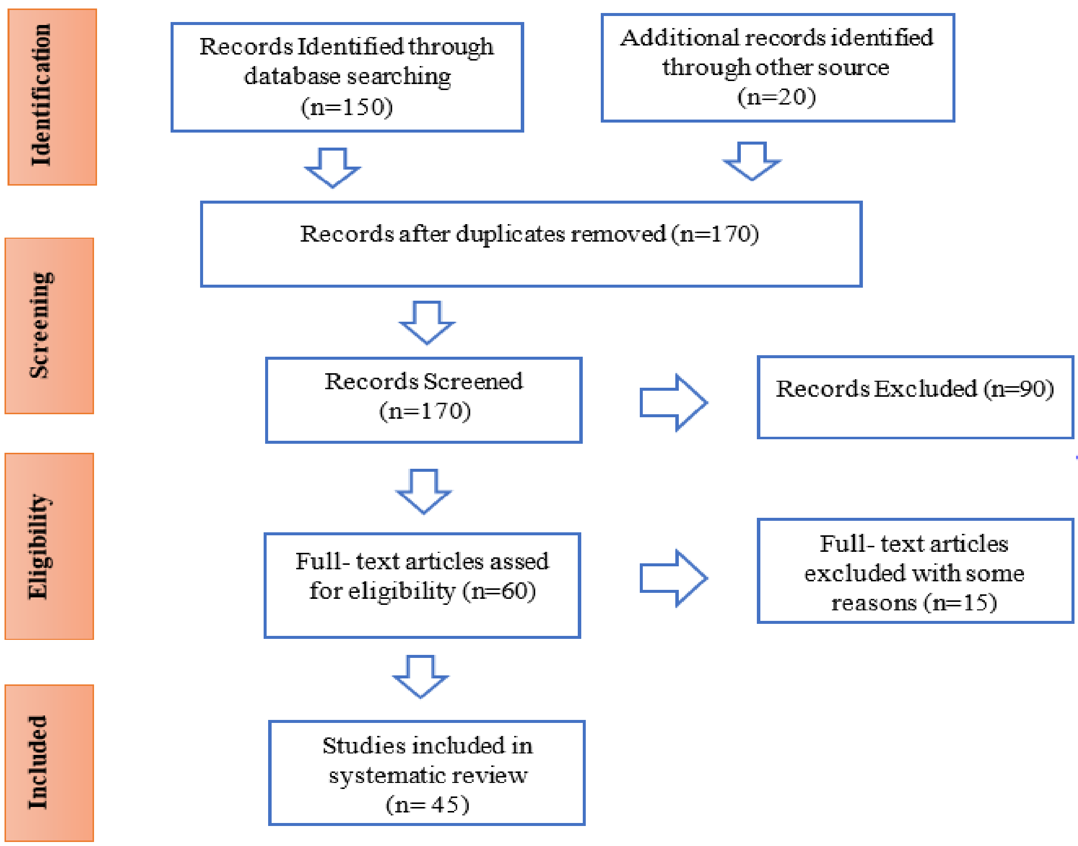

Fig. 2 Flow diagram of the study selection process.

The flowchart lays out a step-by-step procedure for selecting studies for inclusion in the systematic review. A total of 170 records were generated, which included 150 records from a systematic review of online databases, as well as 20 records from other sources, such as hand searches or citation searches, after excluding duplicates. The original 170 records underwent a screening of the titles and abstracts for relevance, and 90 records were excluded from full-text review because they were irrelevant or didn't meet the inclusion criteria. In preparing for the full-text assessment of the 60 returned articles, the research team conducted a review for eligibility based on further criteria, such as study design, populations, interventions, and outcomes. Of the full-text articles, 15 were excluded for various reasons; for example, poor methodological quality, lack of data, or not being aligned with the review question. Therefore, a total of 45 studies met all the inclusion criteria and were included in the systematic review.

Importantly, by employing this described method, the included studies are relevant, high quality, and provide a credible source of evidence, which strengthens the credibility and validity of the systematic review conclusions.

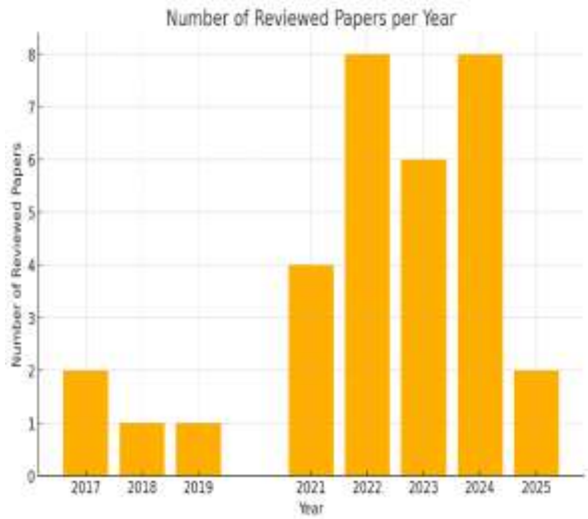

Fig. 3 Diagram of reviewed papers.

The bar chart illustrates the number of reviewed papers published each year from 2017 to 2025. The data shows a generally increasing trend in the number of papers reviewed, with notable peaks in 2022 and 2024, each having 8 papers. The years 2018 and 2019 had the lowest number of reviewed papers, with only 1 each. After a slight drop in 2023 to 6 papers, the count rises again in 2024. The projected data for 2025 shows a decrease to 2 papers. This pattern suggests growing research interest over time, with some fluctuations in recent years.

4. RESULTS AND DISCUSSION

4.1 Authors characteristics

Table 3: Authors and Their Citation Metrics

Author	Citations	Total link strength
bhushan, bharat	17	33
bossuyt, sven	3	30
furlong, cosme	3	30
lin, ming-tzer	3	30
balageas, daniel	5	26
fritzen, claus-peter	5	26
güemes, alfredo	5	26
boller, christian	5	23
chang, fu-kuo	5	23
fujino, yozo	5	23
grattan, k. t. v.	3	23
meggitt, b. t.	3	23
meyer, e.	3	19
inman, daniel j.	3	18
totten, george e.	3	18

bertero, vitelmo v.	8	11
bozorgnia, yousef	8	11
papanikolaou, apostolos	3	9
beck, andré t.	7	7
melchers, robert e.	7	7

This table lists authors along with the number of citations they have received and their total link strength, which likely represents the strength of their connections or influence within a citation network. Bhushan, Bharat leads with the highest citations (17) and the strongest link strength (33), indicating a prominent position in the research field. Several authors share similar citation counts but differ in link strength, suggesting varying degrees of collaboration or impact. The table highlights key contributors and their relative influence based on citations and network connections.

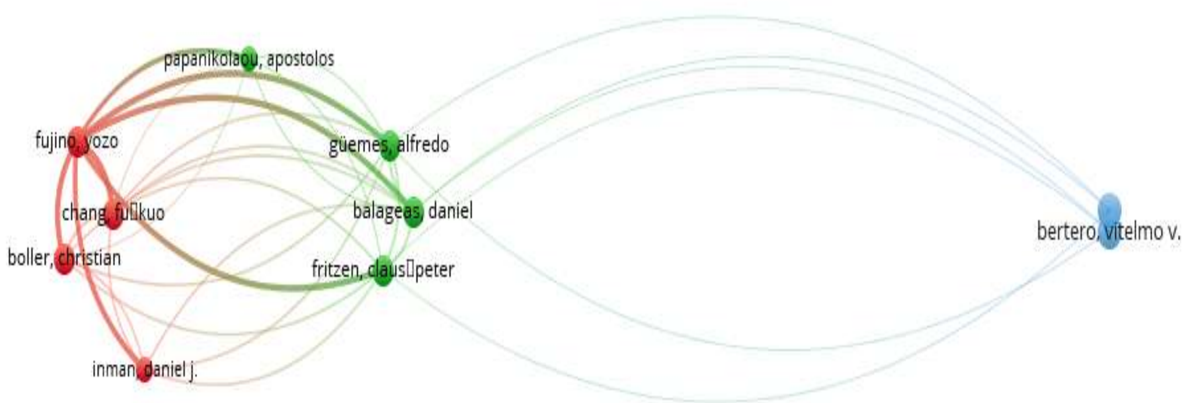

Fig.4 Co-authorship Network Visualization

This figure illustrates the co-authorship relationships among a group of researchers. The nodes represent individual authors, while the edges (lines) between them indicate collaborative publications. Different colors cluster authors into distinct groups or communities based on their collaboration intensity. The red cluster shows a tightly connected group of authors frequently collaborating with each other. The green cluster represents another collaborative group, with links connecting some members to the blue node on the right, indicating broader collaboration. Overall, this network highlights key collaborative patterns and central researchers bridging different groups.

4.2 Collaboration Network

Table 4:

Collaboration Network Among Universities and Research Institutes (2016–2024)

Organization	Documents	Citations	Total link strength
tongji university	18	470	1663
southeast university	13	214	1201
hellenic open university	5	44	837
hohai university	5	145	755

university of bristol	6	331	710
university college london	9	241	666
university of patras	5	16	529
southwest jiaotong university	7	73	518
china earthquake administration	5	147	503
chongqing university	6	12	433
indian institute of technology bombay	6	255	396
pennsylvania state university	5	1294	368
zhejiang university	5	51	295
university of british columbia	6	46	263
hong kong polytechnic university	7	61	254
kyoto university	7	14	253
national technical university of athens	12	12	251
university of naples federico ii	6	9	177
university of birmingham	5	250	162
indian institute of engineering science ...	5	82	140

The table lists various universities along with the number of documents they have published, the citations those documents have received, and their total link strength, which likely represents collaborative or network influence. Tongji University leads in total link strength and citations, indicating a strong research presence and influence. Some universities with fewer documents, like Pennsylvania State University, still have high citation counts, suggesting significant impact per publication. This data helps identify institutions with notable research productivity and influence in their fields

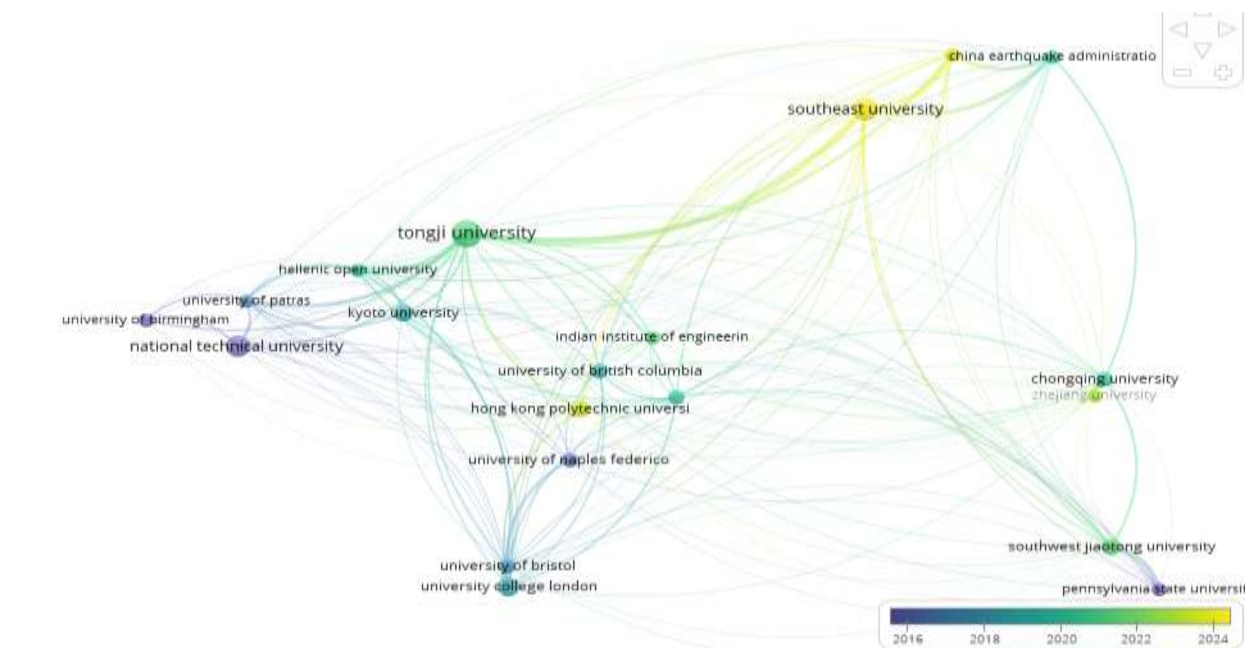

Fig. 5 Collaboration Network Among Universities and Research Institutes (2016–2024)

The figure illustrates a network map representing collaborations among various universities and research institutes from 2016 to 2024. Nodes represent institutions, with size and color indicating the volume and recency of collaborations—the color gradient from blue to yellow reflects the timeline from 2016 to 2024. The edges are representing collaborative links, while thicker and brighter lines represent more recent partnerships or stronger partnerships. The network clusters indicate the institutions with connections, suggesting regional or thematic collaborations, with instances of this in the grouping of institutions around Tongji University and Southeast University. In summary, the map clearly illustrates the ever-changing and developing nature of academic collaboration in recent years.

4.3 Summary of Key Journals

Table 5: Summary of Key Journals in Earthquake Engineering and Related Fields

Source	Documents	Citations	Total link strength
bulletin of earthquake engineering	8	164	571
engineering structures	21	399	560
journal of bridge engineering	7	209	458
encyclopedia of earthquake engineering	147	169	417
structures	20	103	315
structure and infrastructure engineering	7	176	313
soil dynamics and earthquake engineering	7	190	260
reliability engineering & system safety	10	393	256
structural safety	6	154	223
geotechnical, geological and earthquake engineering	13	116	199

The table contains the major journals related to earthquake engineering and safety of structures, with possible research output, and impact. The "Documents" column indicates the number of published papers and "Citations" indicates how frequent those papers are cited to assert their impact. The "Total link strength" gives an indication of the strength of links or collaboration amongst these sources. Notably, the Encyclopedia of Earthquake Engineering has the highest number of documents, but Engineering Structures leads in citations and link strength, showing its central role in the field. Overall, these journals collectively represent major contributors to earthquake and structural engineering research.

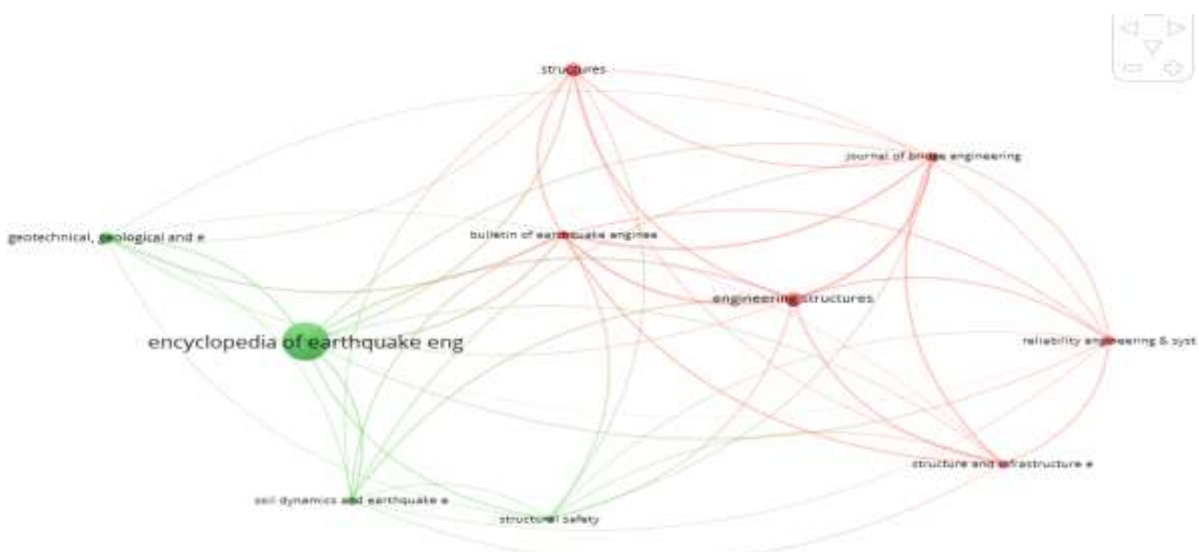

Fig.6 Network Visualization of Earthquake Engineering and Structural Engineering Journals

This figure depicts a network visualization illustrating the relationships between various journals in the fields of earthquake engineering and structural engineering. The nodes represent different journals, with the size of the node indicating the relative importance or influence of each journal. The green and red colors signify different clusters or thematic groups, where green nodes mainly relate to earthquake engineering topics and red nodes to structural engineering topics. The connecting lines indicate citation or collaboration links between journals, showing how knowledge flows and overlaps across these related fields. The largest node, "encyclopedia of earthquake eng," suggests it is a central source in the network.

4.4 Collaboration Strength

Table 6: Research Output and Collaboration Strength by Country

Country	Documents	Citations	Total Link Strength
united states	147	4920	11309
china	117	1885	6521
germany	20	2692	6509
united kingdom	63	2014	5992
italy	43	398	4676
canada	33	252	4516
india	34	567	4227
iran	31	441	4080
japan	24	199	4042
austria	7	140	3946

This table summarizes the research output and collaboration metrics of various countries. The "Documents" column indicates the number of research papers published, while "Citations" reflects how often these papers have been cited by other researchers. The "Total Link Strength" measures the extent of collaborative connections between countries. The United States leads significantly in all three categories, showing its dominant role in research production and international collaboration. Countries like China, Germany, and the United Kingdom also have strong research influence and collaboration networks, while smaller contributors like Austria and Japan have lower but notable engagement. This data helps highlight global research dynamics and partnerships.

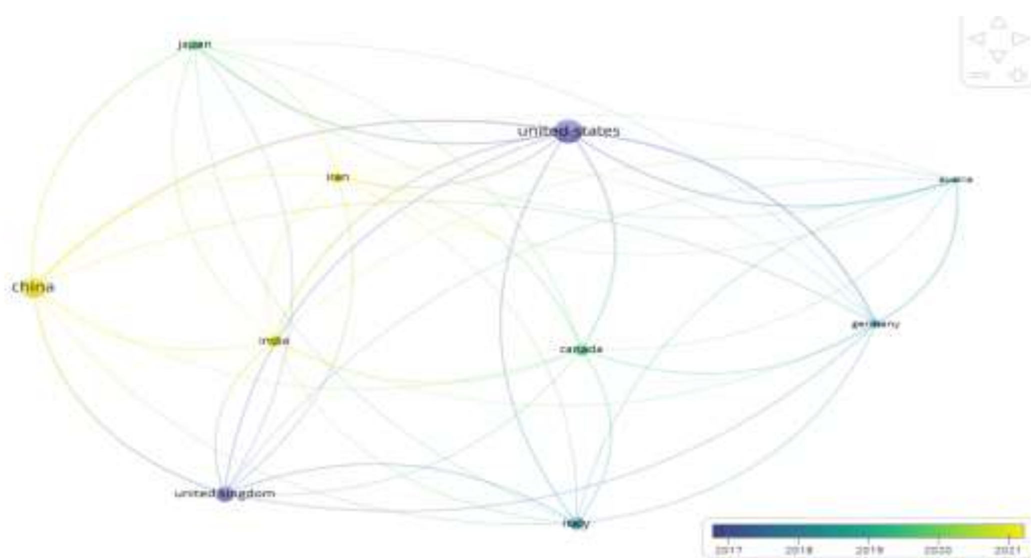

Fig.7 International Collaboration Network Over Time (2017-2021)

The image is a network of international collaborations between countries from 2017 to 2021. Nodes will show countries with edges demonstrating the collaborated links. The edges have a degradation of color from blue (2017) to yellow (2021), as the edges represent the calendar year of collaborations. The nodes of the US, China, and Japan appear to be the relatively clear centre points of the network with many connections from the various other nodes, representing those significant roles for collaborative research. The changing representations in the networks suggest an increase in our cooperation as we approach the present time, with connections in the last years focused on developments which involved countries like China and India. This type of image represents a helpful tool to visualize international partnerships and the complexity of collaboration in the years prior.

5. CONCLUSION

This study presents a thorough numerical and mathematical fragility assessment of bridge structures with a focus on fatigue damage from cyclical non-linear loading like blast effects, vehicle traffic, and natural environmental loading. The investigations overtly state the importance of considering fatigue damage when conducting safety assessments of bridges, especially for cable-stayed and suspension bridges, which often face limited structural redundancy when affected by intense dynamic loading. By incorporating fatigue damage mechanisms into fragility models, this research provides a better predictor of predicted deterioration of structural systems and failure probabilities, filling a void that static or linear analyses have overlooked. The review of literature indicates that there are sound theories regarding the mechanics of fatigue damage and ways of modelling fatigue through numerical methods, but there is an immediate need for multi-hazard fragility frameworks that combine fatigue with blast, seismic, and other dynamic loading effects.

The development of probabilistic fragility curves considering fatigue indices and real-time monitoring represent advancements towards a predictive and adaptive maintenance program, in which predictive maintenance programs persistently have challenges with respect to computational intensity, availability of data, and validation of models.

The collaboration network analysis pointed out some vertices that were particularly impactful, for example, Tongji University and important countries, notably the United States and China that have been facilitating research on bridge fragility derived from dynamic loads. The co-authorship and international collaboration networks also exhibit the importance of interdisciplinary and regional connections for addressing complicated issues of infrastructure resiliency. The networks also highlight key venues, such as Engineering Structures and the Encyclopedia of Earthquake Engineering, which present the most important platforms to advance knowledge dissemination of bridge fragility under impact conditions by providing a global audience, while research trends are evolving towards integrating emerging technologies such as machine learning and structural health monitoring into fragility assessment protocols. Ultimately, this study suggests the need to incorporate fatigue damage due to repeated non-linear loads when conducting a bridge fragility assessment in order to advance the safety and resiliency of bridges. Future research focus should include the development of multi-hazard models, further investigation of real-time data and monitoring systems integration and improved validation processes to facilitate development of effective predictive tools. This will support effective bridge design, maintenance, or regulatory practices to protect critical infrastructure from emerging dynamic threats and extend lifespan of bridges.

6. FUTURE SCOPE

Based on the full fragility assessment framework developed in this report, future research can undertake multi-hazards modelling by assessing fatigue, blast, seismic, and environmental loads simultaneously, and introducing a multi-hazard assessment to derive more representative states of the real world. The sustainability of measurement systems, as discussed here, along with the integration of real-time structural health monitoring (SHM) systems and machine learning algorithms could provide future dynamic and adaptive fragility assessment opportunities, along with improving operational maintenance, longevity, and predicting additional damage. If numerical models could enjoy considerable improvement in computational efficiency, and if we could develop data networks to verify models, we could hopefully resolve some challenges to both verification and scaling challenges can lead to fragmentation of research programs and misunderstandings among researchers concerned with it. Future research should pursue the effects of novel materials and subsequently novel structures in the context of fatigue resistance, fragility, and the impacts of performance. Equally, international research collaborations should be developed to enhance emerging guidelines, regulations, and options to handle the uncertainties, insufficiencies, and vulnerabilities attributable to fatigue. Ultimately, these efforts are directed towards building smarter more resilient bridge infrastructures capable of withstanding dynamically evolving threats over longer service lives.

Statements and Declarations

Ethical Approval

"The submitted work is original and not have been published elsewhere in any form or language (partially or in full), unless the new work concerns an expansion of previous work."

Consent to Participate

"Informed consent was obtained from all individual participants included in the study."

Consent to Publish

"The authors affirm that human research participants provided informed consent for publication of the research study to the journal."

Author Contributions

"All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Rina Kumari, Prof S. S Mishra] and [Rina Kumari]. The first draft of the manuscript was written by [Prof. Ruchi Patira] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript."

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Competing Interests

"The authors have no relevant financial or non-financial interests to disclose."

Availability of data and materials

"The authors confirm that the data supporting the findings of this study are available within the article."

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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