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Review Paper: Monitoring Steel Bridges With Natural Frequency

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Abstrak

Analisis beban dinamis adalah salah satu metode untuk memantau kesehatan struktur jembatan baja. Analisis ini menghasilkan frekuensi alami dan rasio redaman. Kegagalan struktural akibat beban dinamis terjadi ketika frekuensi eksternal sejajar dengan frekuensi alami. Hal ini menunjukkan pentingnya pemantauan kesehatan struktural. Penelitian ekstensif telah dilakukan pada topik tersebut. Pemetaan penelitian menggunakan metode bibliometrik dan scientometrik dapat membantu menganalisis kesenjangan penelitian. Metode analisis bibliometrik mencakup tren dokumen, jenis publikasi, negara asal dan produktivitas dokumen, serta relevansi dan dampak publikasi. Analisis scientometrik menggunakan VOS Viewer untuk memetakan dan menganalisis kolaborasi dalam penelitian. Studi ini bertujuan untuk menggambarkan hubungan antara publikasi, kata kunci, dan tren dalam studi pemantauan kesehatan struktur jembatan baja dalam dekade terakhir (2015-2025). Pengumpulan data dari Scopus mengungkapkan 54 dokumen terkait selama periode tersebut. Analisis bibliometrik dan scientometrik digunakan untuk mengeksplorasi tren publikasi, kolaborasi antarpenulis dan negara, serta distribusi jenis dokumen. tren menunjukkan peningkatan tajam dalam publikasi pada tahun 2022. Tiongkok menduduki peringkat teratas dalam jumlah publikasi dan artikel ilmiah sebagai jenis dokumen tertinggi. Hal ini menunjukkan perlunya kolaborasi internasional yang lebih luas untuk lebih mengembangkan sistem pemantauan Kesehatan struktur jembatan baja. Studi ini menekankan pentingnya peningkatan pemantauan kesehatan struktural, terutama terkait pengaruh frekuensi alami, yang masih kurang dipelajari.

Kata Kunci: Jembatan Baja; Frekuensi Alami; Pemantauan Kesehatan Struktur

Abstract

Dynamic load analysis is one method for monitoring the health of steel bridge structures. This analysis produces natural frequencies and damping ratios. Structural failure due to dynamic loads occurs when the external frequency aligns with the natural frequency. This demonstrates the importance of structural health monitoring. Extensive research has been conducted on the topic. Research mapping using bibliometric and scientometric methods can help analyze research gaps. Bibliometric analysis methods include document trends, publication types, country of origin and document productivity, as well as publication relevance and impact. Scientometric analysis uses VOS Viewer to map and analyze collaborations in research. This study aims to describe the relationship between publications, keywords, and trends in steel bridge structure health monitoring studies in the last decade (2015-2025). Data collection from Scopus revealed 54 related documents during the period. Bibliometric and scientometric analysis were used to explore publication trends, collaborations between authors and countries, and the *distribution of document types. The trend shows a sharp increase in publications in 2022. China ranked first in the number of publications and scientific articles as the highest document type. This indicates the need for broader international collaboration to further develop steel bridge structure health monitoring systems. This study emphasizes the importance of improving structural health monitoring, especially regarding the influence of natural frequencies, which are still understudied.*

***Keywords**: Stell Beam; Natural Frequency; Structure Health Monitoring*

A. Introduction

Dynamic load analysis is a method for monitoring the structural health of bridges.(Gentile & Pirrò, 2024). Steel structures are commonly used in bridge structures. Dynamic analysis of steel bridges is performed to ensure safety and comfort.(Svendsen et al., 2023). Dynamic analysis produces natural frequency values.(Maes & Lombaert, 2024). Natural frequency is the frequency at which an object vibrates when subjected to free vibration (Emrinaldi & Saktioto, 2016). Structural failure due to dynamic loads has been recorded in bridge structures (Olson et al., 2015). This failure is caused by resonance occurring in the bridge. Resonance occurs when the external frequency has the same value as the natural frequency (Reiterer et al., 2023). This relationship demonstrates the importance of monitoring structural health using natural frequency values. Research related to the natural frequency values of steel in bridge structures has been extensively conducted. The process of mapping research to identify or analyze research gaps in a study can be easily performed using bibliometric and scientometric methods. Bibliometric methods can assist in the analysis of scientific output related to annual document trends, document types, countries of origin, most relevant publications, most influential publications, and also the most productive sources of documents in the field of steel bridge structure health monitoring.

This method has been widely applied to analyze trends in various research fields such as Health (Kocak et al., 2019)(Arshad et al., 2023)(Chen Zhigang; Liu, Shengbo; Tseng, Hung, 2012)(Zhong et al., 2019), environment and disasters (Du et al., 2015)(Jiang et al., 2019)(Olawumi & Chan, 2018), materials and energy (Mao, Zou, et al., 2015)(Mao, Liu, et al., 2015)(Chang et al., 2020)(Jiménez-Islas et al., 2022), education (Chen et al., 2016)(Mingers & Leydesdorff, 2015)(Orduña-Malea & Costas, 2021)(Su & Lee, 2010)(Moral-muñoz et al., 2020), and data monitoring processing engineering (Ali et al., 2022)(Abdul Shahid et al., 2023)(Chanief Rahita et al., 2024)(Mahbubi et al., 2024)(Nindhita et al., 2024). In addition, in more advanced analysis methods, bibliometric methods are often associated with scientometric methods that are able to analyze and map the evolution of knowledge from large data sets (Zhong et al., 2019). The scientometric analysis process is an interactive identical visualization of complex analytical data structures for statistical purposes and interactive visual exploration (Chen Zhigang; Liu, Shengbo; Tseng, Hung, 2012)(Olawumi & Chan, 2018), with the help of one of the software, namely VOS Viewer. This software can be used as a visualization and mapping facility for research collaboration networks in various scientific literatures (Kazemi, 2023)(Chou & Pham, 2013).

Therefore, this study aims to visually illustrate the relationship between publications, keywords, researchers, research countries, and study trends related to health monitoring systems for steel bridge structure using bibliometric (José de Oliveira et al., 2019) and scientometric (Mingers & Leydesdorff, 2015) methods in the last decade (2015-2025). It is hoped that this study can provide a new perspective or research gap for more in-depth and collaborative research on equipment, data processing methods, and health monitoring systems for steel bridge structures. So that the existence of a steel bridge structure health monitoring system can develop following technological trends and have more sophisticated capabilities and accurate results.

B. Research Methods

Research data collection was conducted by extracting publication data from the Scopus database. The code entered into the Scopus database is (title-abs-key (Health monitoring of steel bridge structures)), where "title-abs-key" refers to the article title, abstract, and keywords that function as document search sorters in Scopus (Zhong et al., 2019). The data search was limited to publications from the last decade, namely between 2015 and 2025. The search field was also limited to Engineering.

Meanwhile, document type, language, country, and document source were not limited. The limitation of the time period and specific engineering fields was intended to further define the research and align it with the latest technological developments. From this limitation, 54 documents were searched for further analysis regarding publication trends and relationships between documents using bibliometric and scientometric analysis methods.

Bibliometric analysis is a combination of quantitative and qualitative methods that also incorporate statistical and mathematical methods (Arshad et al., 2023)(Du et al., 2015). Bibliometric method is one of the most widely used methods to determine the development of a particular science, which covers various research topics such as publication trends, authors, topics, and so on (Mao, Liu, et al., 2015)(Mao, Zou, et al., 2015)(Wang et al., 2016). In this study, bibliometric analysis is used to sort large literature collections and analyze research development trends in a particular field (Jiang et al., 2019)(Kazemi, 2023)(Wang et al., 2016)(Sekhar et al., 2021). In this step, the Scopus database is analyzed for annual document trends, document types, countries of origin, most relevant publications, most influential publications, and most productive document sources in the field of crack monitoring in concrete structures. The data analysis and visualization process uses Microsoft Excel as a processing tool.

The annual document trend analysis process will provide an overview of the development and number of publications on steel bridge structure health monitoring in the past decade, as well as the potential for future growth. Document type classification analysis will greatly assist readers in understanding the diversity of frequently published document types and the depth of research. Regional network analysis serves to indicate which countries are currently actively conducting research on steel bridge structure health monitoring. The most relevant publication analysis serves to display search results from the Scopus database that best match the search keywords. The most influential publication analysis serves to identify which publications serve as basic references for other research related to steel bridge structure health monitoring. Meanwhile, the publisher analysis reveals which publishers are productive and play a role in disseminating the field of steel bridge structure health monitoring. Furthermore, this analysis also identifies potential future research opportunities.

Scientometric analysis is a quantitative analysis method for understanding emerging trends or patterns in the knowledge structure of a research field (Chen Zhigang; Liu, Shengbo; Tseng, Hung, 2012). Scientometric analysis can measure the impact of research based on relationships between research subjects and map the evolution of knowledge from large-scale data sets (Zhong et al., 2019). The process of scientometric analysis is synonymous with mapping data from scientific literature into interactive visualizations of complex data structures for statistical analysis and interactive visual exploration (Chen Zhigang; Liu, Shengbo; Tseng, Hung, 2012)(Olawumi & Chan, 2018). In this study, VOS Viewer software was used to assist the scientometric analysis process (Orduña-Malea & Costas, 2021)(Oyewola & Dada, 2022). This software is widely used for quantitative analysis to produce well-organized, meaningful, and easy-to-understand results (Ali et al., 2022). VOS Viewer software can also be used as a visualization and mapping tool for collaborative research networks across various research fields to analyze the intellectual landscape of various scientific literatures (Jiménez-Islas et al., 2022)(Chou & Pham, 2013)(Kazemi, 2023).

This scientometric analysis using VOS Viewer software will focus on: (1) co-word analysis; (2) co-author analysis; and (3) cluster analysis. Co-word analysis includes an explanation of the identification of the frequency of occurrence of keywords and research topics related to monitoring the health of bridge structures against the influence of natural frequencies, as well as research developments. Co-Author analysis includes a collaborative network between authors, so that writing patterns and partnerships that underlie research related to monitoring the health of steel bridge structures can be identified. Meanwhile, clustering analysis includes the interpretation of keyword networks and relationships between keywords related to various studies on monitoring the health of steel bridge structures. The analysis techniques and settings used in the Vos Viewer software are shown in Table 1. From the table, the results of keyword mapping produced 69 keywords from the limit of words that appear at least 3 times. This limit aims to further clarify the level of relationship between keywords in the analyzed documents. Meanwhile, the results of author mapping produced 204 authors from the limit of appearing at least 1 document. Table 1 displays the Limitations on the scientometric analysis used

Tabel 1. VOS viewer limitation method

Assesment	Consideration	
	Keyword	Author
Analysis type	Co-occurrence	Co-authorship
Counting Method	Full counting	Full counting
Units of Analysis	All keywords	All Authors
Minimum occurrence	3	1
Result outcomes	69	204

C. Result and Discussion

Research and publications related to the health monitoring of steel bridge structures have experienced quite rapid development over the years. A search of 54 documents in the Scopus database reveals several scientific maps based on the number of documents per year, document type, author's country of origin, and keyword occurrences. Co-authorship analysis can reveal collaboration patterns between countries and institutions. This section outlines the following analytical aspects: (4.1) Annual publication trend analysis; (4.2) Regional network analysis; (4.3) Co-authorship analysis; (4.4) Most contributing documents and sources; (4.5) Distribution of document types; and (4.6) Keyword and hotspot clustering.

1. Results Analysis of Annual Publication Trends

From the Scopus database extraction results, 54 documents on steel bridge structural health monitoring in the Engineering field were obtained between 2015 and 2025. To provide an overview of research developments in this field, the annual distribution of publications related to structural health monitoring on steel bridges indexed by Scopus is presented in Figure 1.

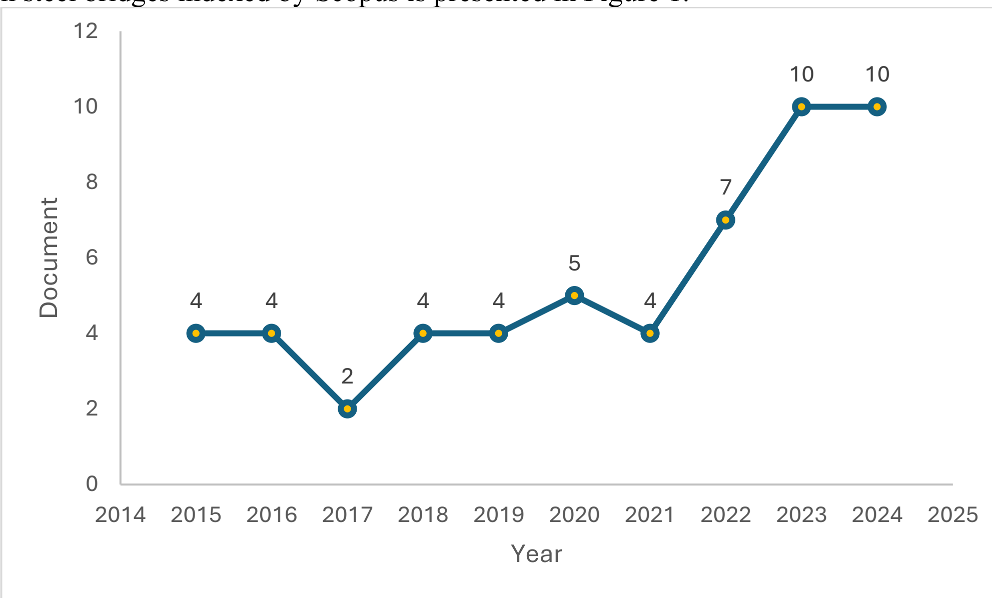

Figure 1. Number of Papers in a Year

As shown in Figure 1, publication trends indicate that research activity from 2015 to 2021 remained relatively limited. Fluctuations in the number of publications, which remained within the low range, indicate that structural health monitoring of steel bridges was not yet a major focus within the engineering community during that period.

Significant changes began to emerge in 2022, marked by a sharp increase in the number of publications. This increase demonstrates growing attention to the development of more advanced structural monitoring systems, in line with growing global awareness of infrastructure safety, aging bridge assets, and the need for data-driven condition analysis.

Scientific productivity peaked in 2023 and 2024, each with a peak publication count of 10 papers. This reflects the accelerated maturity of the research field, driven by advances in sensor technology, the use of artificial intelligence in structural evaluation, and the demand for continuous bridge condition monitoring to support more reliable infrastructure management. Overall, the sharp increase over the past three years confirms that research on structural health monitoring of steel bridges is increasingly relevant and urgent.

2. Regional Network Analysis

A country's contribution to research in the field of structural health monitoring on steel bridges can help authors in developing research in that field. This is because the information can increase the depth of the discussion of researchers in that field. Based on data obtained from Scopus, global contributions to structural health monitoring research on steel bridges can be identified, the distribution is presented based on the number of publications from the author's country of origin in the last 10 years. This visualization provides a comprehensive overview of countries that play an active role in the development of this field, as presented in Figure 2.

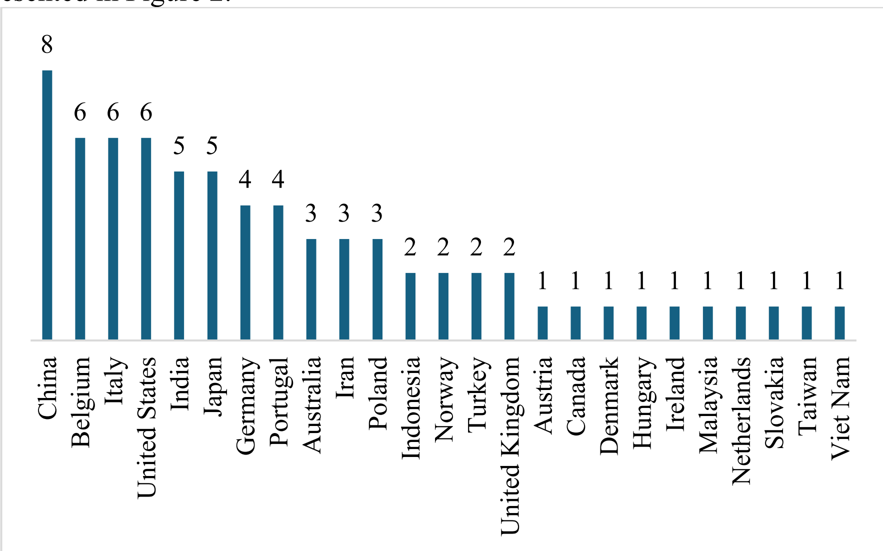

Figure 2. Number of Papers in a Country

Figure 2 shows that the largest contribution to publications related to structural health monitoring of steel bridges came from China, with a total of eight documents. This position indicates China's dominant role in the development of structural monitoring technology and methods, in line with the massive construction and maintenance of bridge infrastructure in that country.

Middle-sized contributing countries, such as Belgium, Italy, and the United States, each produced six documents. This was followed by India and Japan with five documents, and Germany and Portugal with four documents. The number of publications from these countries reflects their strong research capacity and the high level of attention paid to the reliability and safety of steel bridges.

The contributions from Australia, Iran, and Poland, each with three documents, and Indonesia, Norway, and Turkey with two documents, demonstrate that research on this topic has attracted widespread interest, albeit at varying intensities. Meanwhile, other countries, such as Austria, Canada, Denmark, Hungary, Ireland, Malaysia, the Netherlands, Slovakia, Taiwan, and Vietnam, contributed more limited contributions, each with one document.

Overall, the distribution of these publications demonstrates that research on the health monitoring of steel bridge structures is global, involving both developed and developing countries. The dominance of several countries with a high number of publications also indicates the existence of leading research centers that drive the development of science and technology in this field.

Furthermore, scientific collaboration between countries related to structural health monitoring research on steel bridges is crucial. This can increase the depth of content and continuity among researchers in this field. To understand the patterns of scientific collaboration in structural health monitoring research on steel bridges, the network of inter-country connections was analyzed through bibliometric mapping, as shown in Figure 3.

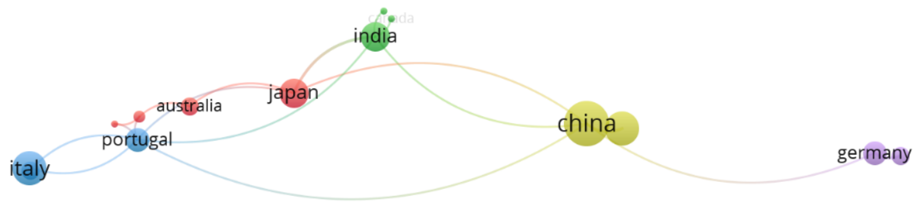

Figure 3. Inter-Country Research Linkages

As seen in Figure 3, the collaborative network structure indicates that China serves as a central node in the map of inter-country research linkages. The large node size and high number of connections indicate China's strong involvement in international collaboration and its significant contribution to knowledge production in the field of structural health monitoring of steel bridges.

India and Japan also appear to be important nodes in the network, as evidenced by their strategic locations and the numerous links connecting them to China and several other countries. This pattern indicates that India and Japan serve as collaborative bridges connecting several research clusters, strengthening scientific integration in this field.

Furthermore, a small cluster involving Italy, Portugal, and Australia indicates a more limited but still significant regional collaboration supporting the diversification of scientific contributions. Conversely, Germany's relatively isolated position from the main cluster indicates that while the country contributes, its collaborative involvement is not as strong as that of the countries forming the network's hub.

Overall, the collaborative network pattern in Figure 3 indicates that research on structural health monitoring of steel bridges is concentrated in a few key countries, acting as catalysts for global knowledge development. This network structure also emphasizes the importance of international collaboration in driving innovation and research quality in the field of infrastructure engineering.

Thus, based on the analysis and visualization of the countries participating in the development of research on the health monitoring of steel bridge structures, there remains a significant opportunity for international research collaboration and the exchange of new ideas between countries on a broader scale. This will allow for further development and accuracy of research related to the health monitoring of steel bridge structures.

3. Co-Authorship Analysis

To identify researchers who have made the most significant contributions to the study of natural frequencies in steel bridges, a collaborative network analysis of the authors was conducted and visualized in Figure 4.

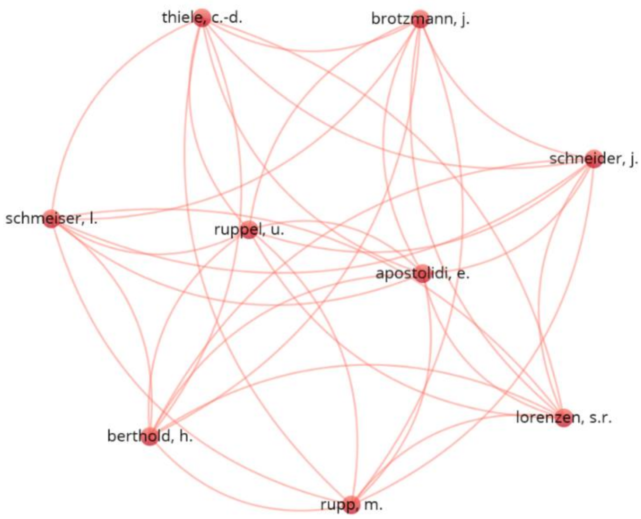

Figure 4. The Most Researchers in The Field of Natural Frequencies of Steel Bridges

Figure 4 shows that the author collaboration network is densely developed, with several researchers acting as key nodes in knowledge exchange. Researchers such as Thiele, C.-D., Brotzmann, J., and Schneider, J. appear to dominate the network, as indicated by their central positions and relatively large number of connections between authors. This reflects their role as active contributors and key drivers in research on the natural frequency of steel bridges.

Ruppel, U. and Apostolidis, E. are also in the network with a high degree of connectivity, indicating that they contribute to strengthening scientific integration through cross-research collaboration. The presence of other authors such as Berthold, H., Schneider, I., Lorenzen, S.R., and Rupp, M. completes the network structure with contributions that, while not as significant as those of the core nodes, are still significant in enriching the development of this research topic.

In general, the connectivity pattern in Figure 4 indicates that research on the natural frequency of steel bridges is built through close, distributed collaboration within a large cluster of authors. The high density of connections indicates that the field thrives through the intense exchange of ideas, the sharing of experimental methods, and collaboration on repeated scientific publications. This finding underscores the importance of collaborative networks in enhancing the quality and depth of research on the dynamics of steel bridge structures.

To obtain a more comprehensive picture of the most influential researchers in the study of the natural frequency of steel bridges, an author impact analysis based on frequency of appearance and scientific relevance is shown in Figure 5.

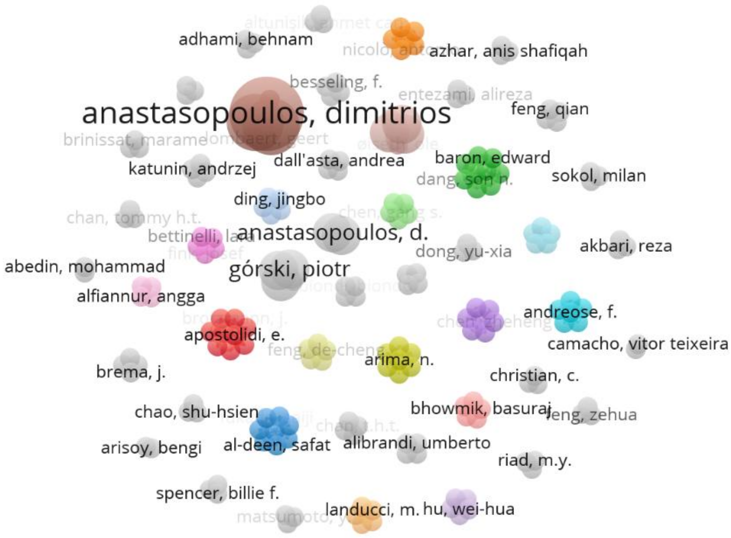

Figure 5. The Most Researchers in The Field of Natural Frequencies of Steel Bridges

As shown in Figure 5, Anastasopoulos emerges as the most influential researcher in the field of natural frequencies of steel bridges. This is reflected in the highly dominant node size, indicating a high number of publications and citation frequency. Anastasopoulos's central position also indicates his role as a leading figure, widely referenced in studies of structural dynamics and vibration behavior in steel bridges.

Anastasopoulos has conducted extensive research in the field of structural health monitoring using vibration-based monitoring (VBM) methods, which examine the effects of natural frequencies, damping ratios, and modes on the temperature of steel bridges.

Furthermore, Górski, Piotr, and Anastasopoulos, D. (different entities in the database) demonstrate a significant level of influence, with relatively large nodes located close to the center of the network. This pattern reflects the active contributions of both researchers in expanding the understanding of structural dynamics phenomena and natural frequency measurement techniques in bridge systems.

Other scattered colored nodes, such as Andreose, F., Apostolidis, E., Bhomwik, Basuraing, and Spencer, B.F., indicate the presence of a group of researchers with medium influence contributing to a specific topic within the same domain. Meanwhile, researchers with fewer nodes are located on the outer ring of the network, indicating more limited contributions or less intense involvement in related publications.

Overall, the distribution pattern in Figure 5 indicates that research on the natural frequency of steel bridges is dominated by a few key researchers who serve as core references for the scientific community. This visualization also confirms the hierarchical structure within the scientific network, with a group of highly influential researchers acting as the primary driver of knowledge development in the field of steel bridge structural dynamics.

4. Most Contributing Documents and Sources

Based on the analysis of 54 documents in the field of steel bridge structural health monitoring, the number of academic institutions that have made the most contributions in this field can be identified. The identification of academic institutions that have made the most dominant contributions in the research on the natural frequency of steel bridges, the results of the publication distribution analysis are shown in Figure 6.

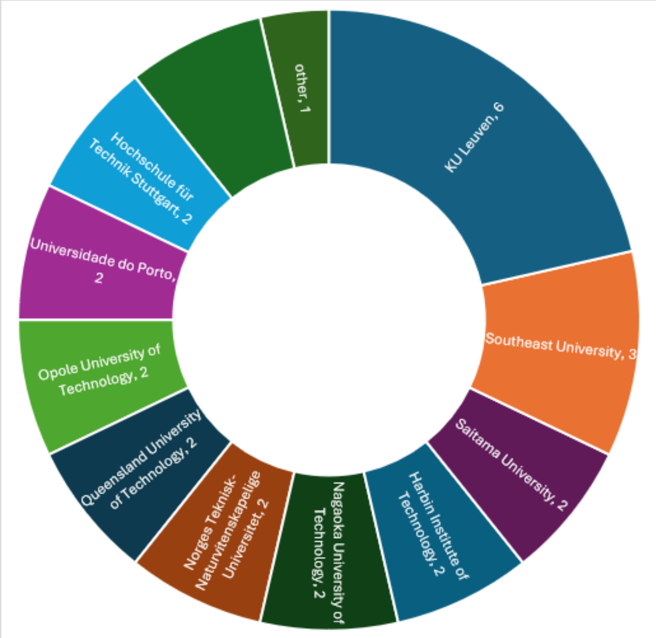

Figure 6. The University With The Most Research on The Natural Frequency of Steel Bridges

Figure 6 shows that KU Leuven is the institution with the largest contribution to research on the natural frequencies of steel bridges, with a total of six publications. This dominance demonstrates the institution's strong research capacity and continued focus on developing structural dynamics studies and natural frequency evaluation methods for steel bridges.

Furthermore, Southeast University ranks second with three publications, indicating its significant role, particularly in experimental measurement-based research and the development of numerical models for structural vibration characteristics. Other universities, such as Saitama University, Harbin Institute of Technology, Nagaoka University of Technology, and Queensland University of Technology—each with two publications—demonstrate equally significant contributions to broadening the understanding of steel bridge dynamics across diverse geographic and methodological contexts.

Several other institutions with two publications, including Opole University of Technology, Universidade do Porto, and Hochschule für Technik Stuttgart, are also identified as part of a consistent global research network studying the natural frequencies of steel structures. Meanwhile, the "other" category reflects the contributions of institutions with a single publication count, indicating that, despite their more limited participation, these contributions still enrich the diversity of research approaches and perspectives.

Overall, the distribution pattern in Figure 6 confirms that research on the natural frequency of steel bridges is concentrated in a few large universities that act as centers of excellence, with support from various other international institutions. This concentration indicates the existence of an organized and collaborative research ecosystem developing a scientific understanding of the dynamic behavior of steel bridges.

To gain a more comprehensive understanding of the focus and direction of research developments related to the natural frequency of steel bridges, a keyword correlation analysis was conducted using a co-occurrence-based bibliometric approach. The visualization in Figure 7 maps the relationships between concepts that most frequently appear together in the global literature.

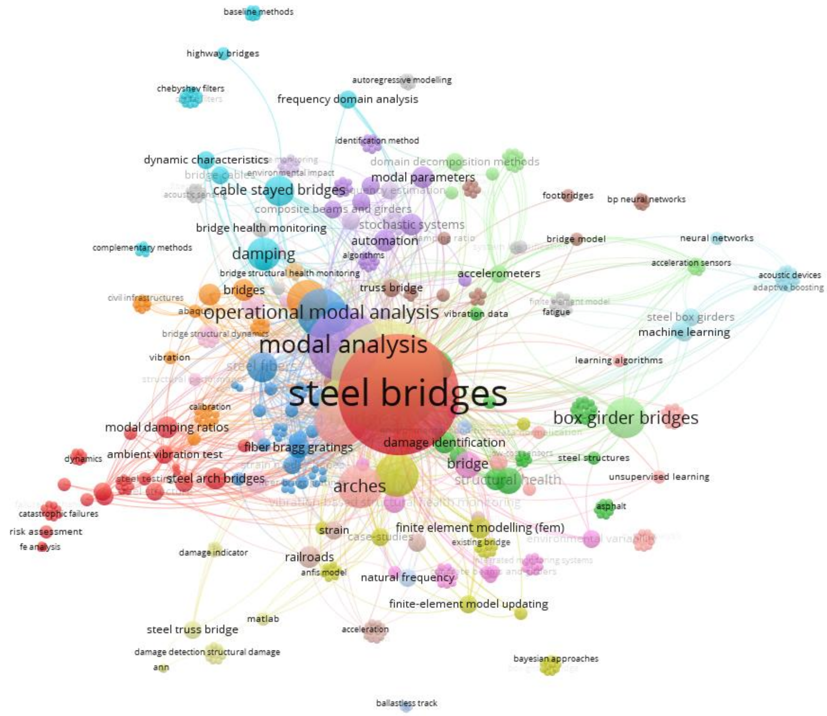

Figure 7. Keyword Correlation in The Paper on Natural Frequency of Steel Bridges

Figure 7 shows a keyword correlation map illustrating the conceptual structure of research on the natural frequencies of steel bridges. The keyword "steel bridges" is centrally located with the largest node size, indicating its highest degree of occurrence and connectivity within the research network. This confirms that steel bridges are the primary object of study in the dynamics of the structures analyzed.

The terms "modal analysis" and "operational modal analysis" emerge as large clusters closely related to the main keyword. This correlation reflects that modal analysis methods—both experimental and operational—are the dominant approaches for measuring and characterizing the natural frequencies of steel structures. The keywords "damping," "damage identification," and "finite element modeling (FEM)" also form significant nodes, indicating that research focuses not only on determining natural frequencies but also on the effects of damping, damage detection, and numerical model integration.

Furthermore, other clusters such as "cable-stayed bridges," "box girder bridges," and "truss bridges" indicate that the concept of natural frequency is not limited to one type of structure but extends to various steel bridge configurations. The emergence of terms like "health monitoring," "accelerometers," "vibration data," and "machine learning" highlights a new trend toward utilizing modern sensor technology and intelligent approaches to monitoring bridge dynamic performance.

Overall, this keyword correlation map demonstrates that research on the natural frequency of steel bridges is developing within a multidisciplinary ecosystem involving modal analysis, structural dynamics, damage detection, numerical modeling, and monitoring technology. The network structure in Figure 7 highlights the integration of classical vibration theory-based approaches with modern data-driven and machine learning methods, which together shape contemporary research directions in this field.

5. Document Type Distribution

Of all the document types contained in the Scopus database related to the health monitoring of steel bridge structures, three types cover this topic. These document types are divided into articles, conference papers, and book chapters. An analysis of these document types is presented in Figure 8.

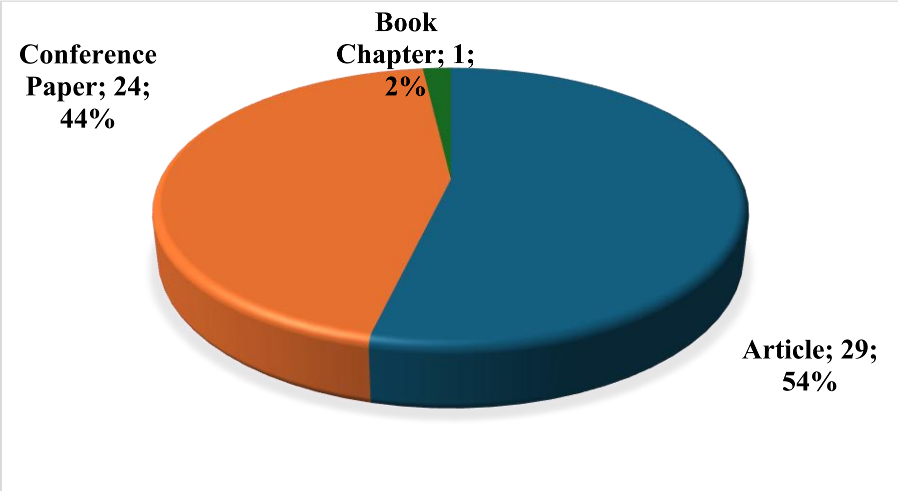

Figure 8. Types of Natural Frequency Documents For Steel Bridges Available in Scopus

Figure 8 shows that publications on the natural frequency of steel bridges are dominated by journal articles, accounting for 54% of the total. This percentage indicates that research in this field tends to be published in scientific articles that have undergone a rigorous peer-review process, ensuring their quality and scientific validity.

Conference papers account for the second largest share, at 44%. The high contribution of publications in the form of conference proceedings indicates that the topic of the natural frequency of steel bridges is an actively discussed topic in international scientific forums. This is common in civil engineering and structural dynamics, where conferences are often the primary medium for communicating the latest findings before they are further developed into journal articles.

Book chapters account for only 2% of the total publications, indicating that discussion of this topic is still rarely included in book chapters. This relatively small number may indicate that the literature on the natural frequency of steel bridges focuses more on contributions based on experimental and numerical research, which are generally more suitable for publication in articles or proceedings.

Overall, the distribution in Figure 8 confirms that research on the natural frequencies of steel bridges is developing along two main paths—journal articles with in-depth scientific contributions and conference proceedings presenting the latest innovations—while contributions in the form of book chapters are still limited.

6. Challenges Perpective and Future Directions

The results of a systematic literature review on natural frequencies in steel bridges indicate that research on this topic is dominated by strong collaborative networks among European and Asian researchers, with key figures, such as Anastassopoulos and Górski, playing a central role in the production of publications and scientific networks. Universities such as KU Leuven and Southeastern University also appear to be the most productive institutions, reflecting the concentration of research in countries with strong traditions in structural dynamics and bridge engineering. Keyword correlations indicate that "steel bridge," "modal analysis," "operational modal analysis," "damping," and "damage identification" are the main focuses, confirming that natural frequency research focuses not only on basic dynamic characteristics but also on the application of damage identification methods and finite element modeling. Furthermore, the types of publications are dominated by journal articles and conference proceedings, indicating that this field is still very actively developing and is constantly updated through international scientific forums. From a researcher's perspective, these findings indicate that the study of natural frequencies in steel bridges is evolving towards an increasingly sophisticated integration of experimental and numerical methods, with a growing emphasis on early damage detection and condition-based maintenance. This confirms the relevance of further research that combines modal analysis, variations in cross-section geometry, the influence of openings, and support conditions to gain a more comprehensive understanding of the dynamic response of steel structures.

D. Conclusion

This study presents a comprehensive bibliometric and scientometric analysis of the development of "steel bridge monitoring with natural frequency" published by Scopus over the past decade (2015-2025). This research includes an analysis of annual document trends, keyword networks, author networks, affiliate networks, country networks, sources, and document types. Scientometric methods, using VOS viewer software, are applied to analyze and visualize the relationships between keywords, authors, countries, and affiliated institutions/organizations.Of the 54 documents analyzed, the publication trend tends to increase year-on-year, although it cannot yet be said to be stable. This is due to current research trends that focus more on methods and equipment frequently used in monitoring the health of steel bridge structures, as well as the integration of real-time monitoring systems through collaboration utilizing advances in digital technology.

Twenty-five countries are developing research on crack monitoring in concrete structures, with China being the most productive in terms of publications. The mapping results indicate that collaboration between affiliates or countries remains low. Therefore, opportunities for broader international research collaboration remain wide open for the development of more sophisticated and accurate monitoring devices, methods, and systems.

Analysis shows that articles dominate the document type distribution, accounting for 54%. This is likely because most research related to the health monitoring of steel bridge structures is based on field tests using equipment, and the data is then processed to draw conclusions about the condition of the structures under study.

In future research, monitoring the health of steel bridge structures by examining the influence of natural frequencies is still very rare. Fewer than 100 documents have been indexed by Scopus in the last decade. This presents a challenge for authors interested in conducting research in this area to further improve their research. It is hoped that this study will facilitate researchers to collaborate to increase knowledge in this field, especially with researchers from China who have conducted extensive research in related fields. This research still has much room for development, with more in-depth analysis. Analysis can be conducted using more than one title so that the documents obtained can be more varied and the analysis can be more detailed.

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Reference

Abdul Shahid, M. D., Mohd Hashim, M. H., Mohd Fadzil, N., Ahmad Rushdi, M. H., Al-Fakih, A., & Muda, M. F. (2023). A bibliometric analysis on the relevancies of artificial neural networks (ANN) techniques in offshore engineering. *Cogent Engineering*, *10*(1).

Ali, L., Alnajjar, F., Khan, W., Serhani, M. A., & Al Jassmi, H. (2022). Bibliometric Analysis and Review of Deep Learning-Based Crack Detection Literature Published between 2010 and 2022. *Buildings*, *12*(4).

Arshad, M., Qamar, A. M., Missen, M. M. S., Lodhi, A. A., & Surya Prasath, V. B. (2023). Global Trends and Collaborations in Dengue Virus Research: A Scientometric and Bibliometric Overview (1872–2019). *International Journal of Design and Nature and Ecodynamics*, *18*(6), 1539–1548.

Chang, X., Zhang, R., Xiao, Y., Chen, X., Zhang, X., & Liu, G. (2020). Mapping of publications on asphalt pavement and bitumen materials: A bibliometric review. *Construction and Building Materials*, *234*, 117370.

Chanief Rahita, A., Zaki, A., Nugroho, G., & Yadi, S. (2024). Internet of Things (IoT) in Structural Health Monitoring: A Decade of Research Trends. *Instrumentation Mesure Metrologie*, *23*(2), 123–139.

Chen Zhigang; Liu, Shengbo; Tseng, Hung, C. H. (2012). *Expert Opinion on Biological Therapy-Emerging trends in regenerative medicine* . *12*(5), 593–608.

Chen, X., Chen, J., Wu, D., Xie, Y., & Li, J. (2016). Mapping the Research Trends by Co-word Analysis Based on Keywords from Funded Project. *Procedia Computer Science*, *91*(Itqm), 547–555.

Chou, J. S., & Pham, A. D. (2013). Enhanced artificial intelligence for ensemble approach to predicting high performance concrete compressive strength. *Construction and Building Materials*, *49*, 554–563.

Du, H., Li, B., Brown, M. A., Mao, G., Rameezdeen, R., & Chen, H. (2015). Expanding and shifting trends in carbon market research: A quantitative bibliometric study. *Journal of Cleaner Production*, *103*, 104–111.

Emrinaldi, T., & Saktioto. (2016). Penentuan Nilai Regangan Jembatan Siak I Oleh Kendaraan Bermotor Menggunakan Fiber Bragg Grating. *Jurnal Komunikasi Fisika Indonesia*, 919–926.

Gentile, C., & Pirrò, M. (2024). One-year dynamic monitoring of a steel-concrete composite overpass. *Journal of Physics: Conference Series*, *2647*(4).

Jiang, Y., Ritchie, B. W., & Benckendorff, P. (2019). Bibliometric visualisation: an application in tourism crisis and disaster management research. *Current Issues in Tourism*, *22*(16), 1925–1957.

Jiménez-Islas, D., Pérez-Romero, M. E., de la Cruz Del Río-Rama, M., & Flores-Romero, M. B. (2022). Mapping Research Trends in Publications Related to Bio-Jet Fuel: A Scientometric Review. *International Journal of Design and Nature and Ecodynamics*, *17*(1), 1–8.

José de Oliveira, O., Francisco da Silva, F., Juliani, F., César Ferreira Motta Barbosa, L., & Vieira Nunhes, T. (2019). Bibliometric Method for Mapping the State-of-the-Art and Identifying Research Gaps and Trends in Literature: An Essential Instrument to Support the Development of Scientific Projects. *Scientometrics Recent Advances*, 1–20.

Kazemi, R. (2023). Artificial intelligence techniques in advanced concrete technology: A comprehensive survey on 10 years research trend. *Engineering Reports*, *5*(9), 1–71.

Kocak, M., García-Zorita, C., Marugán-Lázaro, S., Çakır, M. P., & Sanz-Casado, E. (2019). Mapping and clustering analysis on neuroscience literature in Turkey: a bibliometric analysis from 2000 to 2017. *Scientometrics*, *121*(3), 1339–1366.

Maes, K., & Lombaert, G. (2024). Mode tracking for a steel railway bridge in presence of changing support conditions. *Journal of Physics: Conference Series*, *2647*(18).

Mahbubi, K., Zaki, A., & Nugroho, G. (2024). Bibliometric and Scientometric Trends in Structural Health Monitoring Using Fiber-Optic Sensors: A Comprehensive Review. *Journal of Civil and Hydraulic Engineering*, *2*(1), 51–64.

Mao, G., Liu, X., Du, H., Zuo, J., & Wang, L. (2015). Way forward for alternative energy research: A bibliometric analysis during 1994-2013. *Renewable and Sustainable Energy Reviews*, *48*, 276–286.

Mao, G., Zou, H., Chen, G., Du, H., & Zuo, J. (2015). Past, current and future of biomass energy research: A bibliometric analysis. *Renewable and Sustainable Energy Reviews*, *52*, 1823–1833.

Mingers, J., & Leydesdorff, L. (2015). A review of theory and practice in scientometrics. *European Journal of Operational Research*, *246*(1), 1–19.

Moral-muñoz, J. A., Herrera-viedma, E., Santisteban-espejo, A., Cobo, M. J., Herrera-viedma, E., Santisteban-espejo, A., & Cobo, M. J. (2020). 77520-Texto del artículo-249046-3-10-20200304.pdf. *El Profesional de La Informa- Ción*, *29*, 1–20.

Nindhita, K. W., Zaki, A., & Nugroho, G. (2024). Mapping Publications of Cracks Monitoring in Concrete Structures: Bibliometric and Scientometric Review in 2013-2023. *Annales de Chimie: Science Des Materiaux*, *48*(4), 467–479.

Olawumi, T. O., & Chan, D. W. M. (2018). A scientometric review of global research on sustainability and sustainable development. *Journal of Cleaner Production*, *183*, 231–250.

Olson, D. W., Wolf, S. F., & Hook, J. M. (2015). The Tacoma Narrows Bridge collapse. *Physics Today*, *68*(11), 64–65.

Orduña-Malea, E., & Costas, R. (2021). Link-based approach to study scientific software usage: the case of VOSviewer. In *Scientometrics* (Vol. 126, Issue 9). Springer International Publishing.

Oyewola, D. O., & Dada, E. G. (2022). Exploring machine learning: a scientometrics approach using bibliometrix and VOSviewer. *SN Applied Sciences*, *4*(5).

Reiterer, M., Bettinelli, L., Schellander, J., Stollwitzer, A., & Fink, J. (2023). Application of Vehicle-Based Indirect Structural Health Monitoring Method to Railway Bridges—Simulation and In Situ Test. *Applied Sciences (Switzerland)*, *13*(19).
Sekhar, R., Sharma, D., & Shah, P. (2021). State of the art in metal matrix composites research: A bibliometric analysis. *Applied System Innovation*, *4*(4), 1–43. https://doi.org/10.3390/asi4040086
Su, H. N., & Lee, P. C. (2010). Mapping knowledge structure by keyword co-occurrence: A first look at journal papers in Technology Foresight. *Scientometrics*, *85*(1), 65–79.
Svendsen, B. T., Øiseth, O., Frøseth, G. T., & Rønnquist, A. (2023). A hybrid structural health monitoring approach for damage detection in steel bridges under simulated environmental conditions using numerical and experimental data. *Structural Health Monitoring*, *22*(1), 540–561.
Wang, Y., Lai, N., Zuo, J., Chen, G., & Du, H. (2016). Characteristics and trends of research on waste-to-energy incineration: A bibliometric analysis, 1999–2015. *Renewable and Sustainable Energy Reviews*, *66*, 95–104.
Zhong, B., Wu, H., Li, H., Sepasgozar, S., Luo, H., & He, L. (2019). A scientometric analysis and critical review of construction related ontology research. *Automation in Construction*, *101*(December 2018), 17–31.