Review Article

Exploring the Emerging Evolution Trends of Probabilistic Service Life Prediction of Reinforced Concrete Structures in the Chloride Environment by Scientometric Analysis

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To reveal the global picture and emerging evolution trends with sufficiently large literature data of RC structure's service life prediction, especially the time to corrosion initiation, the scientometric analysis on the corresponding evolution trends was performed by using visualization software CiteSpace and VOSviewer in this paper. First, the application of CiteSpace and VOSviewer and retrieval strategy for data collection were described. And then, information visualization analysis was carried out based on the papers related to RC structure's service life evaluation from publications number evolution, journal distribution, and authors' contribution. Finally, document cocitation network, cooccurring keywords network, and timeline view of keywords network were conducted to discuss the research hotspots on time to corrosion initiation evaluation of reinforcement. Research results reveal that the number of publications on RC structure's service life evaluation reached its peak in 2011. Besides, Structural Safety is the journal that makes the most significant contributions, and Professor Li CQ is the author with the most contribution score. Moreover, the knowledge body of the time to corrosion initiation prediction consists of six clusters; the high-citation articles in this field mainly focus on the multiple-parameters model and probabilistic reliability method.

1. Introduction

Reinforced concrete (RC) structure is the most common and widely used structural form in the world. It is estimated that about 2 billion tons of reinforced concrete are being produced every year at present [1]. Thus, the safety and durability assessment of RC structures have been widely concerned in the sector of civil engineering [2, 3]. It is evident that, in the early 21st century, engineers were fascinated and indeed obsessed with the safety of RC structures but paid insufficient attention to the durability of RC structures, resulting in premature deterioration of RC structures and a huge investment in maintenance to recover the structural performance. It is worth noting that chloride attack is one of the most important factors affecting RC

structures' durability. For many years, the degradation of RC structures due to chloride penetration has been a major problem for construction engineering (e.g., bridges and harbors). The penetration of chloride ions through concrete cover to steel reinforcement resulting in the corrosion of reinforcing steel is a threat to RC structures, particularly those exposed to marine environments [4–6]. Therefore, the service life evaluation of RC structures under chloride environments has become an important research topic of concrete durability in the latest decades [7–10]. The durability research of RC structures exposed to the chloride environment can be divided into three aspects, including durability design of new structures [11–13], durability evaluation[7, 13], and residual service life prediction of existing structures [14, 15]. At present, although the

developing countries are still in a high-speed development stage of infrastructure construction, the durability problem of existing RC structures has gradually emerged. Therefore, predicting the residual service life of RC structures under a chloride environment is of great significance to the sustainable development of society.

Previously, the residual service life of RC structures was determined by the deterministic method [16, 17]. As there are obvious uncertainties in concrete quality, environmental conditions, and time-dependent diffusivity [18, 19], scholars have generally realized that the service life of RC structures is also a random variable [20–22]. In recent years, probabilistic service life prediction of RC structures based on the stochastic analysis of chloride diffusivity has gained importance [7, 13] by calculating the structural reliability according to the corresponding limit state functions. It is stated that the service life of RC structures under chloride environment can be divided into corrosion initiation, corrosion propagation, and structural failure stages [23, 24]. Once corrosion initiates, the sectional area loss of reinforcement will be accelerated, leading to a reduced loading capacity of RC members. Therefore, the importance of predicting the initiation corrosion time of RC structures exposed to a marine environment is highlighted, resulting in an impressive number of studies on time to corrosion initiation evaluation [25, 26]. Combining the existing relevant literature and its achievements can help grasp the current research hotspots, mainstream viewpoints, and theoretical methods in time.

The literature review is a key methodology in examining the development of research on a specific discipline which can provide a reference for effective analysis in further [27, 28]. Shi et al. [29] reported the recent advances relevant to the effects of mineral admixtures on the durability of concrete in a chloride environment. They suggested that it is necessary to conduct more research on determining chloride diffusion coefficients and chloride thresholds in concrete by more standard, reliable, and rapid test methods. After indicating the importance of incorporating life-cycle concepts into structural design and assessment codes, Biondini and Dan [30] reviewed the main principles, concepts, methods, and strategies for life-cycle assessment of RC structures under uncertainty. Lu and Ba [31] proposed a simplified model for the instantaneous corrosion rate of steel rebar in a concrete structure without considering temperature and time. They indicated that the measured corrosion rate increased with chloride content since the chloride ions can combine with ferrous ions to form a water-soluble product that can also accelerate the corrosion process. Yuan et al. [32] summarized the influence factors of chloride binding and indicated the significant effect of chloride binding on prolonging the time to corrosion initiation. Khan et al. [33] carried out an overview to highlight the chloride diffusion model development trends in RC structures. Zhang et al. [34] determined the randomness of each parameter which influenced the time to corrosion initiation of reinforcement and analyzed the probability of the time to corrosion initiation. They indicated that the time to corrosion initiation of reinforcement follows a normal distribution and the predicted mean value is consistent well with the actual measured value. Based on the above reviews, it can be obtained that the existing literature review is insufficient, preventing researchers from capturing an overall picture of research evolution and giving a systematic classification.

In order to fill this research gap, classification and optimization of literature materials on probabilistic service life prediction of RC structures is provided through scientometric analysis. As one of the most important emerging research areas in computational sciences and related disciplines, scientometrics focuses on giving description, evaluation, and prediction on the current situation or development trend of a research theme using mathematical and statistical methods [35]. In addition, the information visualization tools based on scientometrics can help researchers distinguish the major academic journals and publications from huge relevant papers [36, 37], understand research status, and identify cutting-edge research areas more objectively and comprehensively.

In this paper, the citation database (Scopus) is used first to identify the journals that have published the most articles on probabilistic service life prediction of RC structures under chloride environments. After data collection, two software tools (CiteSpace and VOSviewer) were adopted to conduct scientometric analysis. The analysis is mainly performed from the following three aspects: (1) distribution and evolution of relevant publication numbers; (2) subject and journal distribution; and (3) prolific authors and their contribution. Finally, a knowledge network analysis is conducted on time to corrosion initiation of reinforcement.

2. Literature Collection and Scientometric Methods

2.1. Literature Collection. Mapping knowledge domain (information visualization) is a hot field of scientometrics, whose accuracy depends on the quality of retrieved literature. Scopus [38, 39] founded in 2004 is the world's largest abstract and citation database of peer-reviewed literature, including scientific journals, books, and conference proceedings, covering research topics across all scientific and technical disciplines. Further, with smart tools to track, analyze, and visualize research, Scopus empowers people to advance science beyond the text. Therefore, in this paper, the collection of relevant literature on probabilistic service life prediction of RC structures was carried out through Scopus. The data is obtained by querying the Scopus by diverse fields, such as topic, author, journal, and timespan. To identify the relevant literature faster and with more accuracy, the following query has been formulated: TITLE-ABS-KEY (chloride AND corrosion AND concrete AND (probabilistic OR probability OR reliability) AND life). Besides, the literature type was limited to "article, conference paper, conference review, book chapter, and review." Finally, a chronological restriction on the articles of the year of 2019 was employed. 367 research results were returned on Scopus. After finding the related publications, their title and abstract were checked to identify the most relevant publications. Then, some irrelevant articles were excluded. The process resulted in 297 articles for final in-depth analysis.

2.2. Introduction to Scientometric and Information Visualization Software. In the context of big data and information visualization, there are many databases that cover research topics across all scientific and technical disciplines with many publications and novel findings. Therefore, it is necessary to introduce an effective technology to analyze these data. As a scientific and empirical study method of science and its outcomes, scientometrics has been an important method of quantifying science and scientific research. The emphasis of scientometrics is placed on investigating the development and mechanism of science by statistical and mathematical methods. Major research issues of scientometrics include the measurement of impact, reference sets of articles to investigate the effect of journals and institutes, understanding scientific citations, mapping scientific fields, and the production of indicators for use in policy and management contexts [34].

Along with the development of scientometric methods, a great deal of information visualization tools were developed and widely used. CiteSpace and VOSviewer are the two representative visualization tools in the scientometric domain. CiteSpace (http//cluster.cis.drexel.e-du/~cchen/citespace/) is designed as a tool for progressive knowledge domain visualization, focusing on finding critical points in developing a field or a domain [40]. CiteSpace provides various functions to facilitate the understanding and interpretation of network patterns and historical patterns, including identifying the fast-growth topical areas, finding citation hotspots in the land of publications, decomposing a network into clusters, automatic labeling clusters with terms from citing articles, geospatial patterns of collaboration, and unique areas of international collaboration. CiteSpace supports structural and temporal analyses of a variety of networks derived from scientific publications, including collaboration networks, author cocitation networks, and document cocitation networks. It also supports networks of hybrid node types such as terms, institutions, and countries, and hybrid link types such as cocitation, cooccurrence, and directed citing links. VOSviewer (http://www.vosviewer.com/) is a software tool for constructing and visualizing bibliometric networks developed by Leiden University [41]. The networks provided by VOSviewer may, for instance, include journals, researchers, or individual publications, and they can be constructed based on citation, bibliographic coupling, cocitation, or coauthorship relations. VOSviewer also offers text mining functionality that can be used to construct and visualize cooccurrence networks of important terms extracted from a body of scientific literature. It is worth noting that VOSviewer offers support for data exported from dimensions, and CiteSpace provides various functions to facilitate the understanding and interpretation of network patterns and historical patterns. In this paper, these two visualization tools (CiteSpace and VOSviewer) were adopted to analyze the relevant literature and understand the science outcomes on probabilistic service life prediction of RC structures.

2.3. Assessment on Authors' Contribution. Identifying the top contributors to a research topic can facilitate researchers to trace the previous achievements and direct the next research. Howard et al. [42] proposed a quantitative method to determine the contribution by calculating the scores of different authors:

$$\text{Score} = \frac{1.5^{n-i}}{\sum_{i=1}^{n} 1.5^{n-i}}, \tag{1}$$

where n is the total number of authors in an article and i represents the author's ordinal position.

However, the important contribution of the corresponding author is out of consideration in equation (1), since sometimes the corresponding author is not the first author, but his/her contribution is not less than that of the first author. Therefore, the authors' contribution should be determined from two conditions: (1) first author = corresponding author and (2) first author ≠ corresponding author. For condition (1), equation (1) can be used to calculate the authors' contribution. Taking articles with authors less than 5 as an example, the scores are shown in Table 1.

For condition (2), to take the contribution of the corresponding author into consideration, it is supposed that the contribution (score) between the corresponding author and the first author is the same, which is the average score of the first and second author. The scores are shown in Table 2.

It is also worth noting that the research influence and impact of the published journal are also important and necessary to evaluate the author's total contribution. Therefore, equation (1) should be modified by considering the journal's research influence degree. Journal Citation Reports (JCR) provides a statistical evaluation of scholarly journals. Based on the impact factors of the year, each discipline classification is divided into four areas, Q1, Q2, Q3, and Q4 on average according to the impact factors of the year. *Q* stands for Quartile in Category. To take the journal's research influence degree into consideration, the Quartile in Category provided by Journal Citation Reports™ is used to calculate the modified score of the author's total contribution. If the Quartile in Category of journal A is Q1, then 5 point is assigned to the paper published in this journal. The point of the journal of Q2, Q3, and Q4 is 4, 3, and 2, respectively. Besides, if a paper is published at a conference, which can also be retrieved on Scopus, then we supposed that the Quartile in Category of the conference paper is Q5, and the point of this conference paper is 1.

The calculation equation for the modified score is shown as follows:

$$\text{Modified Score} = \sum_{1}^{N} \text{Score}_j \times P_j(Q), \tag{2}$$

where N is the number of papers published by the evaluated author, Score_j is the score of jth paper calculated by eq. (1), and $P_j(Q)$ is the point determined by the Quartile in Category provided by Journal Citation Reports™.

TABLE 1: Scores for papers with multiauthors (first author = corresponding author).

Number of authors	Author order				
	1	2	3	4	5
1	1				
2	0.60	0.40			
3	0.47	0.32	0.21		
4	0.42	0.28	0.18	0.12	
5	0.38	0.26	0.17	0.11	0.08

TABLE 2: Scores for papers with multiauthors (first author ≠ corresponding author).

Number of authors	Author order and the position of the corresponding author				
2	1	2*			
	0.50	0.50			
3	1	2	3*		
	0.395	0.21	0.395		
	1	2*	3		
	0.395	0.395	0.21		
4	1	2	3	4*	
	0.35	0.18	0.12	0.35	
	1	2*	3	4	
	0.35	0.35	0.18	0.12	
	1	2	3*	4	
	0.35	0.18	0.35	0.12	
5	1	2	3	4	5*
	0.32	0.17	0.11	0.08	0.32
	1	2*	3	4	5
	0.32	0.32	0.17	0.11	0.08
	1	2	3*	4	5
	0.32	0.17	0.32	0.11	0.08
	1	2	3	4*	5
	0.32	0.17	0.11	0.32	0.08

Note. The figure with * represents the position of the corresponding author.

3. Scientometric Analysis and Visualization of Literature on Probabilistic Service Life Prediction of RC Structures

3.1. Distribution and Evolution of Relevant Publications. Since the 1990s, a large number of studies have indicated that chloride-induced reinforcement corrosion has caused serious durability damage to RC structures and resulted in large economic losses [43–45]. Therefore, scholars have realized the importance and urgency of the durability of RC structures, which has gradually become a research hotspot. According to the database analysis on the evolution of relevant publications per year (Figure 1), it can be observed that probabilistic service life prediction of RC structures is a rapidly growing research topic.

Moreover, Figure 1 shows that research on probabilistic service life prediction of RC structures can be divided into two stages, that is, initial development stage (1993–2009) and rapid development stage (2010–2019). By using the CiteSpace software, cluster analysis is adopted to identify the research development trend changes in the initial and rapid development stages, as shown in Figure 2.

Figure 2(a) suggests that, at the initial development stage (1993–2009), the research concentrates on service prediction of RC structures and investigating the deterioration mechanism. At this stage, Vu and Steward proposed a reliability model to predict the service life of RC structures [46] and got the highest citation frequency. Moreover, the clustering tags have become rich and varied (as shown in Figure 2(b)), much focusing on the reinforced concrete bridges. The main investigation contents are the corrosion initiation of reinforcement and service life of RC structures. Meanwhile, the service life prediction of RC structures by the deterministic method was gradually replaced by the probabilistic method [47, 48].

3.2. Subject and Journal Distribution. The number of publications in each category reflects the research development trends in different domains. To analyze the subject categories distribution of publications on exploring the service life prediction of RC structures in the chloride environment, the subject categories of 297 publications are summarized in Figure 3.

It can be observed from Figure 3 that most of the publications belong to the subject category of engineering (62.28%). In addition, materials science has the second most abundant publication records (20.09%), followed by other
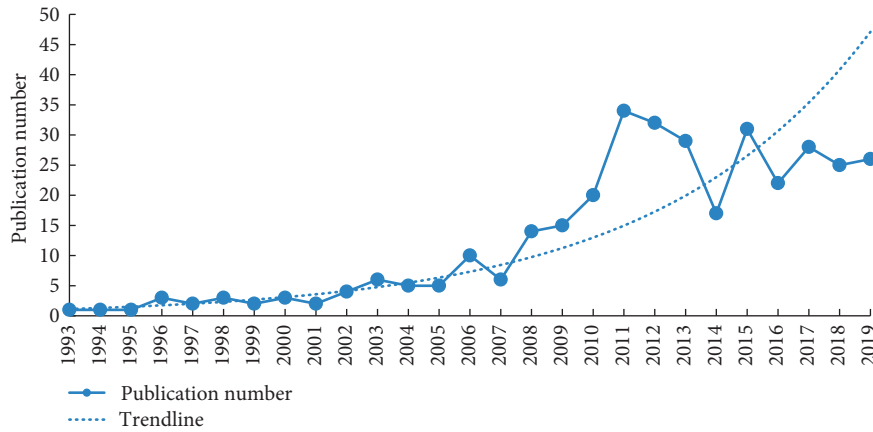
Figure 1: Evolution of relevant publications per year (1993–2019).

(a)

(b)

Figure 2: Cluster analysis on the research focus at different stages. (a) Initial development stage. (b) Rapid development stage.

Engineering 62.28%
Materials Science 20.09%
Enviromental Science 4.02%
Physics and Astronomy 3.35%
Mathematics 2.46%
Computer Sciences 2.01%
Social Sciences 2.01%
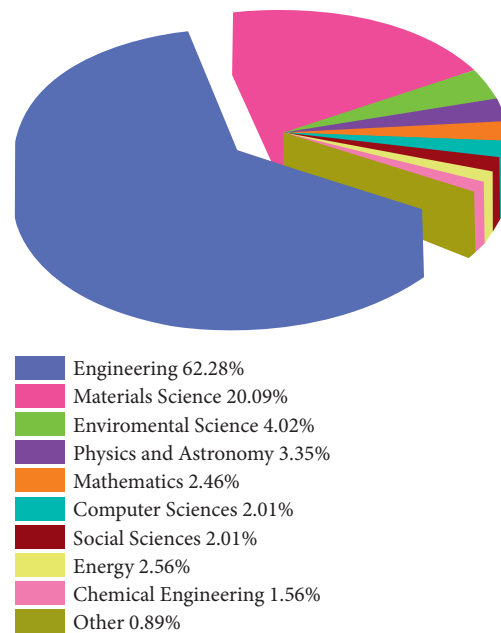Energy 2.56%
Chemical Engineering 1.56%
Other 0.89%

Figure 3: Subject categories of 297 publications on service life prediction of RC structures in the chloride environment.

main categories: environmental science (4.02%), physics and astronomy (3.35%), energy (2.56%), mathematics (2.46%), computer science (2.01%), social sciences (2.01%), and

chemical engineering (1.56%). Thus, it can be concluded that engineering and materials science are the main categories of service life prediction of RC structures in the chloride

environment, indicating that service life prediction of RC structures is mainly investigated from the perspectives of engineering and materials.

Identifying the leading journals in service life prediction of RC structures research can enable researchers to trace the relevant journals rapidly and assist them in publishing their findings on these journals. Therefore, the journals with the most related publications are identified. Figure 4 shows the top 14 leading journals with more than 4 publications.

Figure 4 shows that Construction and Building Materials has the highest number of publications (38 papers), followed by Cement and Concrete Composites which publish 23 articles, Cement and Concrete Research and Structural Safety, which publishes 20 articles, respectively. In addition, to quantitatively analyze the development trend of research on service life prediction of RC structures in the chloride environment in different journals and the obtained degree of concern, an indicator of published ratio is proposed in this paper. The published ratio calculates the published articles in this research topic to the total articles published in one journal. Table 3 gives the statistical information on the publications in corresponding 7 journals from 1998 to 2019.

It can be seen from Table 3 that, during the past 20 years, in the 7 journals as mentioned above, there are 41355 articles published in total and 147 publications concentrate on investigating the service life prediction of RC structures in the chloride environment. Moreover, the ranking of published ratio is different from that of related articles published in different journals. Taking Construction and Building Materials as an example, although it has the highest number of publications (40 papers), its published ratio is low (less than the average ratio of 0.36%) due to the large total publications in Construction and Building Materials. A similar phenomenon also exists in Engineering Structures. Besides, Structural Safety has the largest published ratio (2.04%), followed by Structure and Infrastructure Engineering (0.99%) and Cement and Concrete Research (0.60%).

3.3. Prolific Authors and Their Contribution. Figure 5 gives the most prolific authors who contributed to the research topic with at least 5 articles.

The most representative author is Dan M. Frangopol, from Lehigh University in the United States with 12 articles, followed by Mark G. Stewart from Newcastle University in Australia with 11 publications.

It is worth noting that there are some relationships and connections between different authors. Therefore, it is necessary to create a coauthorship network to explore the relationships and connections of authors in the publications. Figure 6 shows a coauthorship network in which the articles were published from 1993 to 2019. In the coauthorship network, the size of each node reflects the number of published articles, and the line width of the link represents the level of the collaborative relationship between authors.

It can be observed from Figure 6 that there is an obvious collaborative relationship between authors. Therefore, the article number alone cannot represent the authors' contribution. According to the method to assess authors'

contribution mentioned in Section 2.3, the scores of different authors and the corresponding modified scores are calculated, as shown in Table 4.

It can be seen from Table 4 that Li CQ has the highest contribution score and modified score, followed by Mark G. Stewart, although their article numbers are less than that of Dan M. Frangopol, indicating a more concentrated research focus of Li CQ and Mark G. Stewart. In addition, the authors with higher contribution scores and modified scores are all from developed countries.

4. Knowledge Network and Visualization of Study on Time to Corrosion Initiation Evaluation of Reinforcement

4.1. Document Cocitation Network with CiteSpace. In order to obtain the knowledge network and identify the important research achievements for the research of time to corrosion initiation of reinforcement, 158 most relevant papers were determined through the second literature screening. Based on the citation data retrieved from the Scopus database, the order of cited research papers on time to corrosion initiation from 1993 to 2019 was determined according to the citation frequency. The generation of a document cocitation network includes the following steps: (1) timespan of 26-years between 1993 and 2019 was divided into 26 1-year time slices; (2) in each time partition, the top 50 cocited documents were selected; and (3) path algorithm was used to clip the documents in single time partition and total time span to generate document cocitation network.

Table 5 summarizes the highly cited documents from the 158 most relevant papers. It can be seen that the most cited paper comes from Cement and Concrete Research; the highly cited and highly centralized papers mainly come from the journals such as Structural Safety and Engineering Structures.

Figure 7 shows the document cocitation network, including 201 nodes (which represent the analysis objects) and 592 links (which represent the cocitation relationship). It is worth noting that there are nodes with different sizes and colors. A node with a larger size denotes a higher occurrence (citation) frequency of the document. Besides, the color and thickness of the ring around the node indicate the occurrence frequency of documents in different periods. For example, the node with a purple ring has a higher centrality and is more important in the knowledge network than the nodes with other colors. Moreover, the thicknesses of links between adjacent nodes are different, which indicates the levels of the cocitation relationship in one year. According to the cocitation frequency of documents, papers with the highest influence related to time to corrosion initiation of reinforcement in RC structure under chloride environment can be obtained.

It can be observed from Figure 7 that the article with the largest node is written by Val and Trapper [49] (Probabilistic evaluation of initiation time of chloride-induced corrosion). This paper presented a model with two mechanisms for chloride ingress into concrete (diffusion and convection).
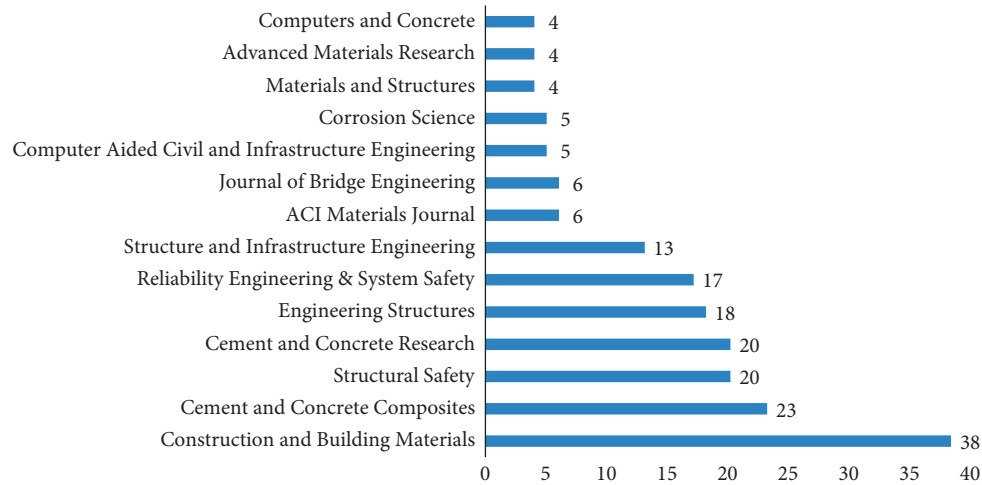
Figure 4: Top 14 journals for research on service life prediction of RC structures in chloride environment.

A probabilistic evaluation of the time to corrosion initiation was conducted, respectively, for a reinforced concrete (RC) wall (1D problem) and an RC column (2D problem) in a marine environment. Research results indicated that, for the same concrete cover depth, the corrosion initiation probability in reinforcing bars of RC column is much higher than that of wall, demonstrating the importance of 2D modeling for predicting time to corrosion initiation more correctly. This paper can be used as a reference in exploring the multidimensional chloride diffusion model in concrete. However, their paper did not consider the spatial variability of related parameters (such as humidity, chloride diffusion coefficient, surface chloride concentration, and concrete cover thickness) and possible correlation among different parameters.

Moreover, in Figure 7, the article with the highest centrality is written by Stewart and Mullard [50] (Spatial time-dependent reliability analysis of corrosion damage and the timing of first repair for RC structures). A spatial time-dependent reliability analysis considering the random spatial variability of concrete material properties, concrete cover, and surface chloride concentration was presented in this paper to predict the likelihood of cracking for RC bridge deck exposed to chloride attack. Allowing the extent of damage as a function of time, a reinforced concrete surface was discretized into a large number of smaller elements, and random field methods were used to simulate the variability of the concrete damage over the entire area; thus, corrosion initiation and propagation, crack initiation, and crack growth can be predicted.

In addition, other documents with higher citations are also marked in Figure 7. Obviously, these documents mostly focus on how to modify the mathematical model to predict the time to corrosion initiation and improve the prediction accuracy. Tang and Gulikers [51] demonstrated that the simplified error function complement (ERFC) solutions might overestimate the service life by orders of magnitude, especially when the age factor of chloride diffusion coefficient is high. Bastidas-Arteaga et al. [47] indicated that the mean value of time to corrosion initiation would decrease when the randomness and seasonal variations of humidity, temperature and surface chloride concentration, and convection are considered and increase when chloride binding is taken into account through establishing a stochastic model of service life prediction, reflecting the importance of considering the random nature of influence parameters for a comprehensive lifetime assessment. Angst et al. [52] reviewed the critical chloride concentration from the definition, influencing parameters and test methods, which is of great reference value since critical chloride concentration is one of the most important parameters affecting the time to corrosion initiation of reinforcement.

4.2. Network of Cooccurring Keywords with VOSviewer.

Keywords can accurately reflect the basic information of the core research content of a paper. Therefore, the changes of structures or subjects and the research hotspot or development trend in a certain field can be analyzed by keywords quantification and visualization through some scientific models. With the help of the VOSviewer software (version 1.6.8), a cooccurrence keywords analysis based on bibliographic data has been performed. To create a clear and representative network, a minimum occurrence for each keyword should be defined at first. In this paper, the keywords are required to occur at least ten times. Eventually, 133 keywords have met the requirement, as shown in Figure 8.

After eliminating the invalid records, six keywords are employed more than 60 times: corrosion (180), model (160), concrete structure (91), chloride (116), uncertainty (78), and service life (78). And the keyword groups corresponding to the main research topics are presented in Table 6 (some keywords with strong correlation are only listed).

The results show that model, corrosion, and chloride are the main keywords with the highest cooccurrence frequency in the past 20 years, and there is a certain correlation between the keywords. For example, chloride ingress, diffusion coefficient, and corrosion initiation can all be related to the model and grouped into the first group (model).

TABLE 3: Statistical information on the publications in corresponding journals (1998–2019).

| Journal	Metric	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Total
All journals	Total articles	601	691	699	736	754	881	886	942	942	1137	1255	1382	1335	1528	2064	2461	2624	2824	3458	3990	4960	5205	**41355**
	Related articles	5	4	2	3	3	2	3	3	3	6	11	13	9	4	8	7	10	10	15	10	12	4	**147**
	Ratio (%)	0.83	0.58	0.29	0.41	0.40	0.23	0.34	0.32	0.32	0.53	0.88	0.94	0.67	0.26	0.39	0.28	0.38	0.35	0.43	0.25	0.33	0.08	**0.36**
Construction and Building Materials	Total articles	50	51	43	51	61	73	96	109	135	265	302	465	353	550	987	1122	1287	1363	1916	2144	2972	2725	**17120**
	Related articles	0	0	0	0	0	0	0	0	0	2	2	3	0	0	3	4	3	3	7	5	6	2	**40**
	Ratio	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.66	0.65	0	0	0.3	0.36	0.23	0.22	0.31	0.23	0.20	0.07	**0.23**
Cement and Concrete Research	Total articles	200	295	282	274	287	315	315	343	275	203	178	155	211	159	190	176	157	215	222	210	196	287	**5145**
	Related articles	0	3	1	1	2	1	1	0	2	1	0	4	2	1	1	0	0	2	2	0	0	2	**26**
	Ratio (%)	0.00	1.02	0.35	0.36	0.35	0.32	0.32	0.00	0.73	0.49	0.00	2.58	0.95	0.63	0.53	0.00	0.00	0.93	0.90	0.00	0.00	0.70	**0.51**
Structural Safety	Total articles	36	27	32	37	24	31	30	29	29	38	56	64	55	42	37	54	53	60	59	69	58	62	**982**
	Related articles	2	1	1	0	1	1	1	1	0	1	3	3	1	0	0	1	1	1	1	0	0	0	**20**
	Ratio (%)	5.56	3.70	3.13	0.00	4.17	3.23	3.33	3.45	0.00	2.63	5.36	4.69	1.82	0.00	0.00	1.85	1.89	1.67	1.69	0.00	0.00	0.00	**0.20**
Cement and Concrete Composites	Total articles	57	85	66	62	74	151	124	134	127	96	126	107	107	131	165	152	170	175	190	188	241	288	**3016**
	Related articles	0	0	0	0	0	0	0	0	1	1	1	1	0	1	2	0	4	3	1	2	1	1	**18**
	Ratio (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.79	1.04	0.79	0.93	0.00	0.76	1.21	0.00	2.35	1.71	0.53	1.06	0.42	0.00	**0.60**
Engineering Structures	Total articles	139	117	170	174	159	175	200	196	208	323	359	317	389	384	424	636	604	612	704	939	1083	1344	**9656**
	Related articles	3	0	0	0	0	0	0	0	0	1	0	1	5	2	1	1	0	0	1	1	1	0	**18**
	Ratio (%)	2.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.00	0.32	1.29	0.52	0.24	0.16	0.00	0.00	0.14	0.11	0.09	0.00	**0.19**
Reliability Engineering and System Safety	Total articles	119	116	106	138	149	136	121	131	168	185	199	232	167	192	173	228	235	284	254	318	293	384	**4328**
	Related articles	0	0	0	2	0	0	1	2	0	0	5	1	0	0	0	0	2	1	1	0	2	0	**17**
	Ratio (%)	0.00	0.00	0.00	1.45	0.00	0.00	0.83	1.53	0.00	0.00	2.51	0.43	0.00	0.00	0.00	0.00	0.85	0.35	0.39	0.00	0.68	0.00	**0.39**
Structure and Infrastructure Engineering	Total articles	0	0	0	0	0	0	0	0	0	27	35	42	53	70	88	93	118	115	113	122	117	115	**1108**
	Related articles	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	1	0	0	3	2	4	0	**11**
	Ratio (%)	—	—	—	—	—	—	—	—	—	3.70	0.00	0.00	1.89	0.00	1.14	1.08	0.00	0.00	2.65	1.64	3.42	0.00	**0.99**
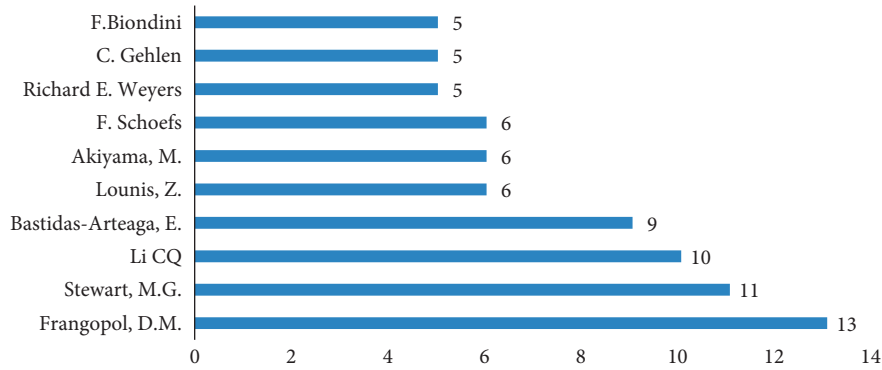
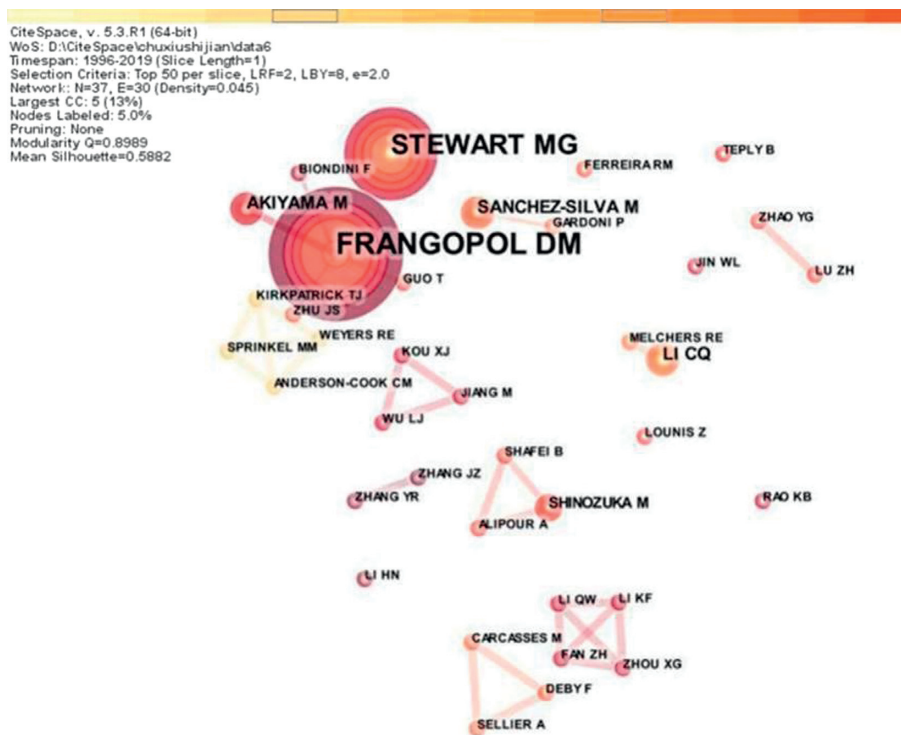FIGURE 5: The most prolific authors with at least 5 publications in databases.

FIGURE 6: Coauthorship network.

TABLE 4: Authors' contribution score and modified score in this research topic.

Author	Organization	Country	Article number	Score	Modified score
Dan M. Frangopol	Lehigh University	USA	13	4.160	11.320
Mark G. Stewart	The University of Newcastle	Australia	11	5.490	18.730
Li CQ	RMIT University	Australia	10	5.770	22.590
E. Bastidas-Arteaga	University of Nantes	France	9	3.715	17.620
Akiyama, M.	Waseda University	Japan	6	2.285	7.660
F. Schoefs	University of Nantes	France	6	1.545	5.060
Z. Lounis	National Research Council Canada	Canada	6	2.790	9.070
Richard E. Weyers	Virginia Polytechnic Institute and State University	USA	5	1.560	5.520
C. Gehlen	Technische Universität München	Germany	5	1.930	3.325
F. Biondini	Politecnico di Milano	Italy	5	2.420	5.700

TABLE 5: Top 8 documents with higher citations on time to corrosion initiation evaluation research.

| Order	Citation frequency	Centrality	Author	Document title	Time	Source journal
1	506	0.08	Ueli Angst	Critical chloride content in reinforced concrete—A review	2009	Cement and Concrete Research
2	198	0.03	Tang Luping	On the mathematics of time-dependent apparent chloride diffusion coefficient in concrete	2007	Cement and Concrete Research
3	145	0.06	Mark G. Stewart	Spatial variability of pitting corrosion and its influence on structural fragility and reliability of RC beams in flexure	2004	Structural Safety
4	135	0.19	Mark G. Stewart	Mechanical behavior of pitting corrosion of flexural and shear reinforcement and its effect on structural reliability of corroding RC beams	2009	Structural Safety
5	118	0.06	Do-Eun Choe	Probabilistic capacity models and seismic fragility estimates for RC columns subject to corrosion	2008	Reliability Engineering and System Safety
6	110	0.22	Mark G. Stewart	Spatial time-dependent reliability analysis of corrosion damage and the timing of first repair for RC structures	2007	Engineering Structures
7	95	0.08	Dimitri V. Val	Probabilistic evaluation of initiation time of chloride-induced corrosion	2008	Reliability Engineering and System Safety
8	91	0.07	E. Bastidas-Arteaga	A comprehensive probabilistic model of chloride ingress in unsaturated concrete	2011	Engineering Structures
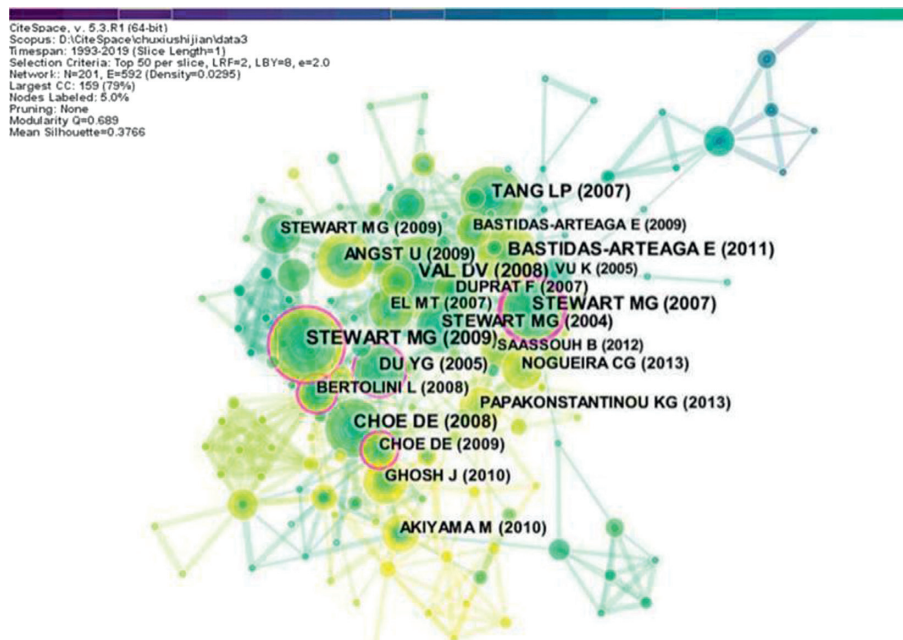
FIGURE 7: Document cocitation network on reinforcement initial corrosion time evaluation research.

4.3. Research Hotspots and Evolutionary Trends on the Time to Corrosion Initiation Evaluation. Based on keyword cooccurring network analysis mentioned in Section 4.2, the research hotspots and evolutionary trends of the time to corrosion initiation in 2000–2019 are presented by the timeline view. Figure 9 indicates the cluster order of evaluating the time to corrosion initiation with the probabilistic method. The cluster number is represented by #0, #1, and so on, and the smaller the number, the larger the cluster size. Afterward, it can be seen that the modularity Q value of 0.4147 is close to 0.5, which means that the division of clusters is relatively reasonable and the average silhouette value is 0.5205 (>0.5), indicating that the homogeneity of these clusters is at a reasonable level. Besides, the focus of the research field needs to be strengthened.

It can be seen from Figure 9 that the main cluster is reliability-based assessment, followed by chloride environment, reinforcement corrosion attack, durability monitoring, spatial correlation, and probabilistic approach. Through cluster analysis of keywords timeline view, it can be concluded that (1) the research hotspot of the initial corrosion time of reinforcement in RC structures under chloride environment has focused on the reliability theory and probability method at the beginning of the 21st century. (2)
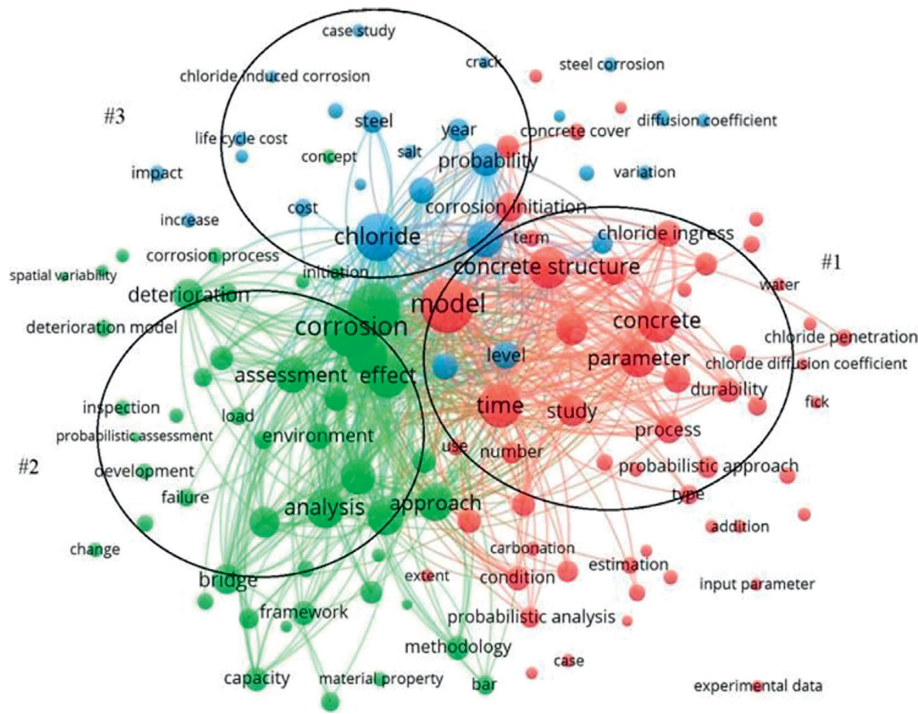
FIGURE 8: Keywords cooccurring network analysis with at least ten occurrences.

TABLE 6: Main keywords and corresponding keyword group.

| Main research topics	Keyword groups
Model	Chloride ingress, diffusion coefficient, corrosion initiation, random variable, probability analysis, and durability
Corrosion	Concrete bridge, reinforcement, RC structure, approach, uncertainty, corrosion rate, corrosion progress, and performance
Chloride	Level, prediction, salt, diffusion coefficient, service life, Monte Carlo simulation, and probabilistic model
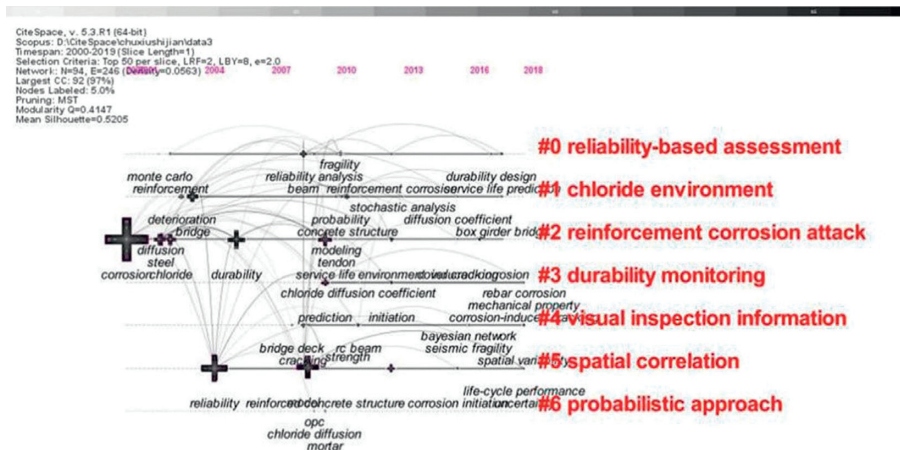
FIGURE 9: Timeline view of keyword on predicting the time to corrosion initiation.

Monte Carlo simulation method is a probabilistic evaluation method which is widely used in the early period; finite element analysis and Bayesian network have been widely used in recent years [53–55]. (3) The spatial variability of chloride diffusion [56, 57] and the sensitivity analysis of the parameters affecting time to corrosion initiation are the evolution trends on the related research [58–60].

5. Conclusions

Probabilistic service life prediction of RC structures in the chloride environment has become a popular research topic of concrete durability, and great efforts have been achieved. This study explores the emerging trends and knowledge network of relevant research by the scientometric analysis. Some highlights in this study are listed as follows:

(1) Scholars have realized the importance of the service life assessment of RC structures in chloride environment at the beginning of the 1990s. Then, the number of annual publications in the early 21st century showed a slight increase and fluctuation trend. From 2009 to now, the probabilistic service life, especially the time to corrosion initiation assessment, has gained wide attention and become a research hotspot.

(2) Significant contributions and influences of prolific authors and journals are identified. The analysis results show that, based on the number of published articles, Construction and Building Materials and Professor Frangopol provided the largest number of papers in the field of probabilistic service life prediction of RC structures. However, Structural Safety and Professor Li CQ were at the top based on the published ratio and authors' contribution score.

(3) Articles with the most cited come from Cement and Concrete Research; the highly cited and highly centralized papers mainly come from the journals such as Structural Safety and Engineering Structures.

(4) Timeline view of the keyword network shows that based on

(5) structural reliability theory, evaluating time to corrosion initiation of reinforcement in RC structure by the probabilistic method is the most important research topic. Finite element analysis and Bayesian network have been the main methods to evaluate the time to corrosion initiation of reinforcement in recent years. In addition, spatial variability and sensitivity analysis of random parameters are hot topics in future research.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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