Damage assessment of RC bridges considering joint impact of corrosion and seismic loads: A Systematic literature review

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Abstract

This paper systematically reviewed 84 journal articles published from 2010 to 2020 and structured the reviewed literature using the following categories: year-wise number of research articles, journals, country, and citations. Through a bibliometric and content review analysis, the present review found that the existing studies have mostly focused on corrosion effects, and less attention was paid to quantifying seismic damage of corroded RC bridges. It is required to develop a damage assessment methodology for corroded RC bridges based on a reliable damage index, which can consider the cumulative effects of repeated loading cycles during earthquakes combining the impact of corrosion.

Keywords: RC bridge; Corrosion; Seismic damage; Damage index; Components; Joint impact.

1. Introduction

The transportation network plays an important role in economic and social development of most countries in the world, and highway bridges are the most critical, and challenging element that make transport easy and fast, and enhance mobility between regions and countries. However, a significant percentage of bridges, particularly for those located in earthquake prone-regions, may face multiple degradation mechanisms, such as fatigue, erosion, and acid attacks on concrete members, carbonation, and chloride-induced corrosion of steel components [1, 2]. Among those, the corrosion deterioration of reinforcement in reinforced concrete (RC) components due to the chloride-ions is a matter of increasing concern [3], which may affect some critical bridge components such as RC columns, steel bearings, RC deck, and steel girders [4]. Over the last decades, a significant number of efforts have been dedicated to study the effects of corrosion on the nonlinear responses of components of RC bridges such as beams, columns, and slabs, under monotonic and cyclic loadings through experimental and numerical studies [5-28]. The results of these studies showed that corrosion of reinforcement bars is a long-term process and may effectively reduce the nonlinear capacity of RC components, which may cause cracking and spalling of the concrete cover, a considerable decrease in the compressive strength of the cracked cover concrete, the cross-sectional area, the mechanical properties and ductility of reinforcement, and loss of bond strength at the reinforcement and concrete interface. These changes in the structural properties of corroded RC components may lead to degradation of the structural stiffness and damping of the structural elements, dynamic characteristics, inelastic behavior and seismic responses of RC bridges under earthquake excitements and consequently, amplify the vulnerability of RC bridge system and components to seismic loads [18-33]. However, a large number of RC bridges are located in the marine environment and earthquake-prone regions. Therefore, recently researchers have tended to study the nonlinear behavior of RC bridge components with various levels of corrosion under cyclic and seismic loadings through deterministic and probabilistic analyses [24-47]. The results of these studies highlighted the importance of considering the influence of chloride-induced corrosion in seismic damage assessment of RC bridges located in the marine environments. The aforementioned studies revealed that although research on seismic damage assessment of corroded RC bridges has matured particularly in the last decade, however, there has been a lack of study on the effects of corrosion on seismic induced damages of RC bridges at component and system levels in a quantifiable degree. In other words, despite many efforts on seismic damage analysis of corroded RC bridges, several potential drawbacks still exist on estimating the damage values and damage levels of system and components of RC bridges considering the simultaneous impact of corrosion deterioration and cumulative effects of repeated loading cycles of earthquakes. As there is no specific overview, to the best of authors' knowledge, of seismic damage assessment of corroded RC bridges regarding damage parameters used for describing the damage levels of bridges at components and system levels, the present contribution tries to fill this gap partly by carrying out a methodological review of the articles published on seismic damage assessment of corroded RC bridges with a focus on their damage evaluation framework and structural damage parameters. This paper mainly aims to highlight the lack of a quantitative damage assessment study on corroded RC bridges and emphasize on the importance and advantages of considering damage indices in the seismic vulnerability studies of RC bridges in the marine environments as future opportunities for advancement.

2. Research methodology

This paper investigates and categorizes the existing literature on seismic damage assessment of corroded RC bridges with a focus on information exchange during the last decade up to 2020 using a quantitative and qualitative research method. Note that although many experimental and numerical studies have been devoted to address corrosion-induced damage or seismic damage of RC bridges individually [3,4,5,7], but the focus toward the impact of corrosion on seismic behavior of RC bridge has grown significantly after 2010 [18,24,29,33,36]. The main objective of this paper is to identify the seismic damage evaluation methodology used for corroded RC bridges and provide an outline regarding the existing literature and justify the need for conducting this study. Research methodology consists of the following steps:

1. Categorizing the research questions and inclusion and exclusion criteria,
2. Collecting relevant articles though systematic search, screening, and filtering the articles regarding the inclusion and exclusion criteria,
3. Gathering relevant information from the included articles,
4. Categorizing and analyzing the significant findings.

In this paper, the bibliometric analysis aims to present a quantitative analysis using statistical methods to study trends of academic publications and citations to assess the performance of the existing efforts and understand their patterns. The process of a systematic bibliometric analysis, which is employed in this paper, is shown in Fig. 1. As observed, the bibliometric analysis includes (1) a keyword research in the Scopus database: a keyword search was conducted in the Scopus database using different keywords including, “Corroded bridge and damage assessment”, “Corroded bridge and seismic damage”, “bridge corrosion and damage assessment”, “bridge corrosion and seismic damage”, “bridge corrosion and damage index”, “bridge corrosion and seismic damage”, “bridge component and damage index and corrosion”, “bridge component and damage and corrosion”, “deterioration and RC bridge” and “deterioration and Reinforced concrete bridge” , which results in 543 Articles. The different search terms/keywords within each search block were combined with the Boolean operator ‘‘OR”. (2) These articles were filtered to select only journal papers and published in English language. This resulted in 266 articles. (3) In third step, we identified the journals by filtering articles that were available in journals with a CiteScore greater than one (CiteScore: “is the number of citations received by a journal in one year to documents published in the three previous years, divided by the number of documents indexed in Scopus published in those same three years”). (4) We conducted additional search in the Web of Science (WoS) database to deal with any limitation in the Scopus database, and combined the results and organized them in one list. (5) Finally 84 academic articles resulted after reviewing full text of all articles.

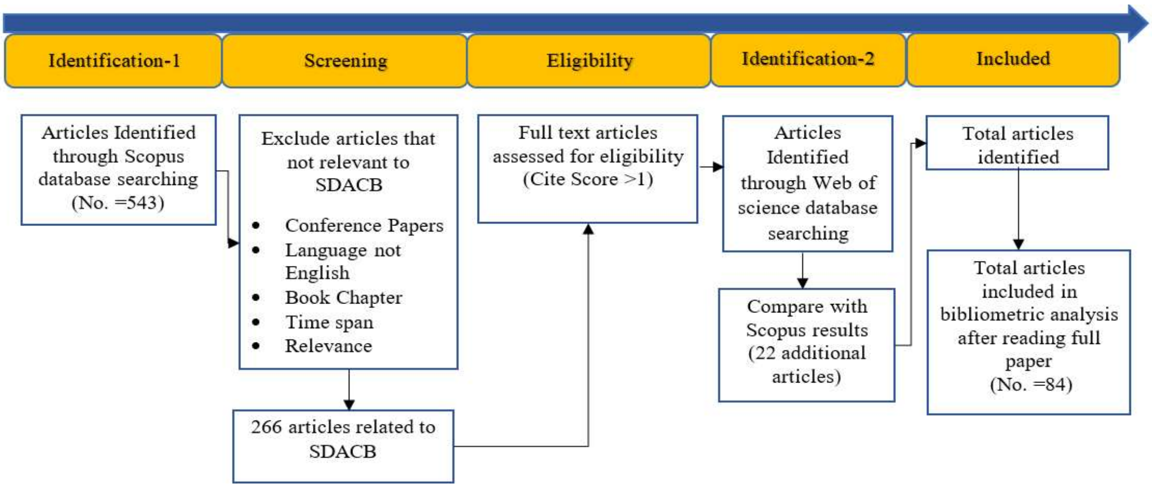


Fig. 1. Flow diagram of selection of articles for bibliometric analysis

3. Descriptive analysis results

3.1 Analysis of articles according to publication years

The analysis of the reviewed articles along various dimensions is provided in this section using tables and figures to summarize the results. The bibliometric analysis results are shown in Fig. 2 and Table 1. It is found from the trend that the number of publications on seismic damage assessment of corroded RC bridges has been noticeably increased during the last decade; from 2 articles in 2010 to 15 articles in 2020. During the period of 2010-2012 the number of articles varied between 2 and 6. According to Fig. 2, the number of the research publications increased to 9 in 2015 and after a gap in 2016, showed a great increase during 2016-2020 and reached 15. Moreover, the results show that about 68% of the publications were released during the last five year, which indicates the increasing interest in the seismic damage assessment of corroded RC bridges.

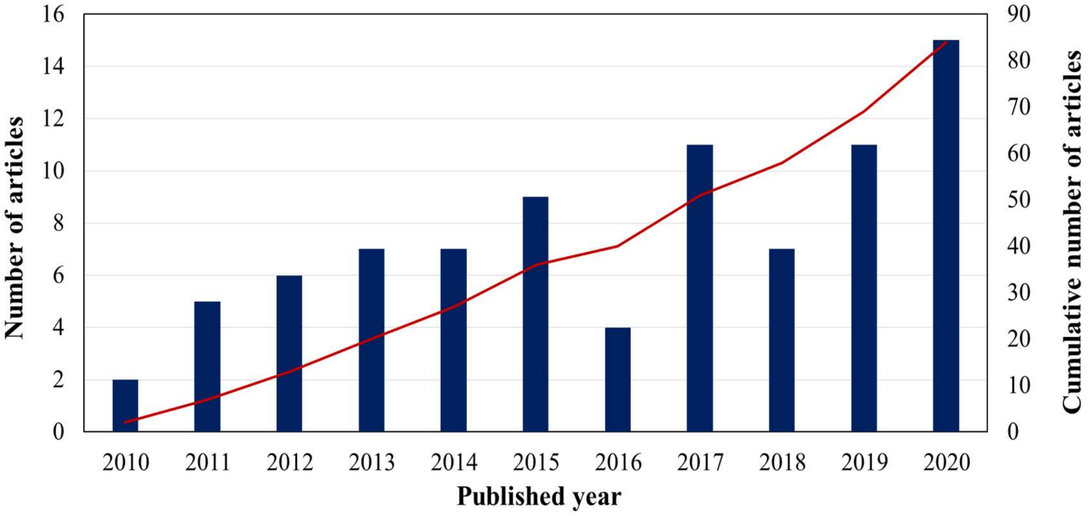


Fig. 2 Yearly wise publications.

3.2 Analysis of articles distributed in various journals

According to Table 1, the bibliometric analysis shows that 84 articles were published across 35 different journals. Moreover, as observed in Table 1 and Fig. 3, the largest number of publications in the field of seismic damage evaluation of corroded RC bridges were conducted in "Construction and Building Materials" with 13.1% of the total articles. This was followed by "Engineering Structures" (11.9%) and "Structure and Infrastructure Engineering Structures" (10.71%) and. These three journals covered 35.71% of the total articles on seismic damage assessment of corroded RC bridges. However, the journal entitled "Journal of Bridge Engineering" published 6 articles and "Journal of Structural Engineering" published 5 articles. This followed by "Earthquake Engineering and Structural Dynamics" and "Bulletin of Earthquake Engineering" published 4 articles for each, whereas "Soil dynamic and Earthquake Engineering" published 3 articles. "International Journal of Structural Integrity" and "International Journal of Structural Stability and Dynamics", "Journal of Earthquake Engineering", "Earthquake Spectra" and "Structures" published 2 for each. The remaining journals' publications were equal to one during the last decade.

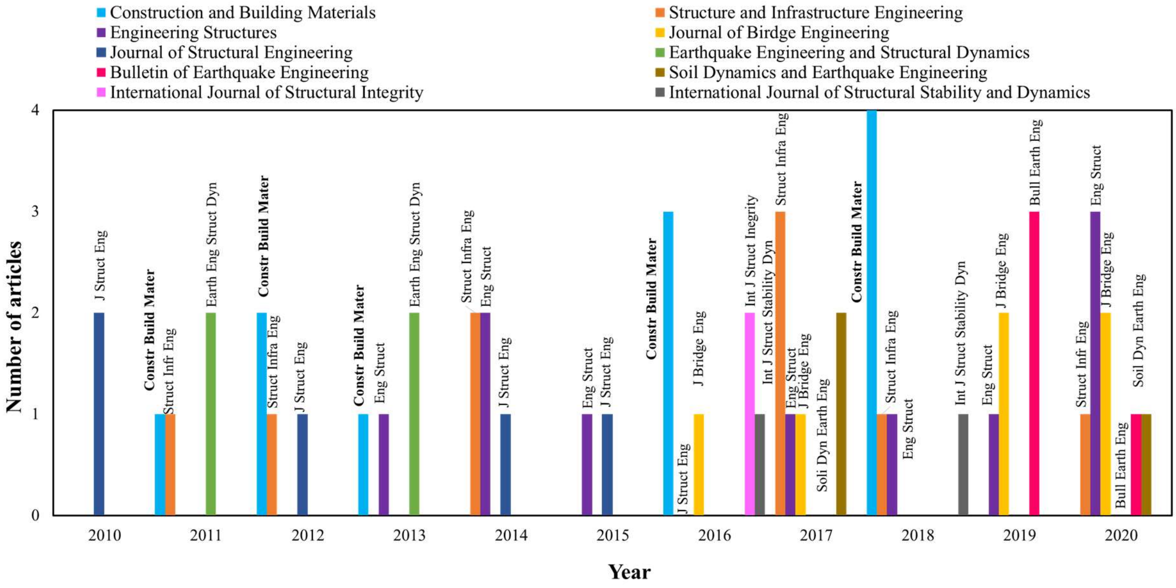


Fig. 3 Publications per year per source (top 10 journals).

Table. 1 Review sources of 35 academic journals and the identified articles during 2010–2020.

	Journal	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	total	%
1	Construction and Building Materials	0	1	2	1	0	0	3	0	4	0	0	11	13.10
2	Engineering Structures	0	0	0	1	2	1	0	1	1	1	3	10	11.90
3	Structure and Infrastructure Engineering	0	1	1	0	2	0	0	3	1	0	1	9	10.71
4	Journal of Bridge Engineering	0	0	0	0	0	0	1	1	0	2	2	6	7.14
5	Journal of Structural Engineering	2	0	1	0	1	1	0	0	0	0	0	5	5.95
6	Earthquake Engineering and Structural Dynamics	0	2	0	2	0	0	0	0	0	0	0	4	4.76
7	Bulletin of Earthquake Engineering	0	0	0	0	0	0	0	0	0	3	1	4	4.76

8	Soil Dynamics and Earthquake Engineering	0	0	0	0	0	0	0	2	0	0	1	3	3.57
9	International Journal of Structural Integrity	0	0	0	0	0	0	2	0	0	0	0	2	2.38
10	International Journal of Structural Stability and Dynamics	0	0	0	0	0	0	1	0	1	0	0	2	2.38
11	Journal of Earthquake Engineering	0	0	0	1	0	0	0	0	0	0	1	2	2.38
12	Structures	0	0	0	0	0	0	0	0	0	0	2	2	2.38
13	Earthquake Spectra	0	0	0	0	1	0	0	1	0	0	0	2	2.38
14	ACI Materials Journal	0	0	0	0	0	0	0	0	0	1	0	1	1.19
15	Bridge Structures	0	0	0	0	0	0	0	0	0	1	0	1	1.19
16	International Journal of Civil Engineering	0	0	0	0	0	0	0	0	1	0	0	1	1.19
17	Reliability Engineering and System Safety	0	0	0	0	0	0	1	0	0	0	0	1	1.19
18	Advances in Structural Engineering	0	0	0	0	0	0	0	0	0	0	1	1	1.19
19	Complexity	0	0	0	0	0	0	0	0	0	1	0	1	1.19
20	Composite Structures	0	0	0	0	0	0	1	0	0	0	0	1	1.19
21	Earthquake and Structures	0	0	1	0	0	0	0	0	0	0	0	1	1.19
22	Earthquake Engineering and Engineering Vibration	0	0	0	0	0	0	0	0	0	1	0	1	1.19
23	Engineering Failure Analysis	0	0	0	0	0	0	0	0	0	0	1	1	1.19
24	Frontiers in Built Environment	0	0	0	0	0	0	0	0	1	0	0	1	1.19
25	International Journal of Corrosion	0	0	0	0	0	0	1	0	0	0	0	1	1.19
26	Journal of Structural Integrity and Maintenance	0	0	0	0	0	0	0	0	0	0	1	1	1.19
27	Natural Hazards	0	0	0	0	1	0	0	0	0	0	0	1	1.19
28	SDHM Structural Durability and Health Monitoring	0	0	0	0	0	0	0	0	0	0	1	1	1.19
29	Structural Engineer	1	0	0	0	0	0	0	0	0	0	0	1	1.19
30	Materials Performance	0	0	1	0	0	0	0	0	0	0	0	1	1.19
31	Reliability Engineering and System Safety	0	0	0	0	0	0	1	0	0	0	0	1	1.19
32	Key Engineering Materials	0	0	0	1	0	0	0	0	0	0	0	1	1.19
33	Advances in Concrete Construction	0	0	0	0	0	0	0	0	0	1	0	1	1.19
34	Advances in Structural Engineering	0	0	0	0	0	0	0	0	0	0	1	1	1.19
35	Earthquake and Structures	0	0	1	0	0	0	0	0	0	0	0	1	1.19

3.3 Analysis of articles according to source country

The bibliometric analysis results indicate that the largest numbers of journals on seismic damage assessment of corroded RC bridges during the last decade have been published in the UK (35.71%), the USA (26.19%), and Netherlands (23.81%) as displayed in Fig. 4. Switzerland and South Korea contribute to about 3.57%, followed by China, Egypt and Singapore contributing 2.38%, 2.38% and 2.38%, respectively. As observed, the UK and USA leading the chart is relevant because the annual cost of corrosion damage to highway bridges in the UK is estimated to be about £1 billion [48] and in the USA is between $64.3 billion and $10.15 billion [49].

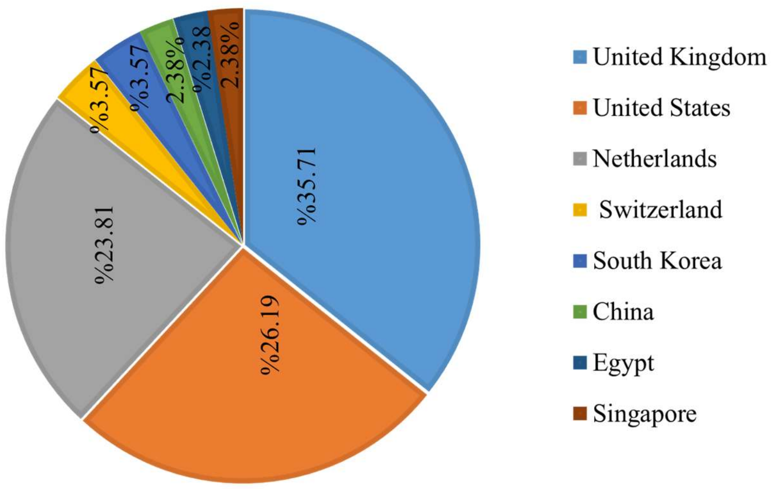


Fig. 4 Distribution of reviewed articles over country.

3.4 Analysis of articles according to citation

Table 2 represents the top ten cited articles in 2010-2020 with respect to the Scopus citation metric. Note that it is clear that the older articles have higher citations but the number of citations is presented to highlight the articles and journals that have been mainly used as the source articles in this research area during the last decade. The most cited articles were published in "Earthquake Engineering and Structural Dynamics", with 138 citations that followed by "Construction and Building Materials" with 125 citations. This followed by the article released by "Earthquake Engineering and Structural Dynamics" with 120 citations. Fig. 5 shows the distribution of the most cited articles over journals. As observed, "Earthquake Engineering and Structural Dynamics" has totally 312 citations and "Construction and Building Materials" has 291 citations.

Table 2. Top ten cited articles in 2010-2020

	Citations	Article	Author	Journal	Year
1	138	Time-variant sustainability assessment of seismically vulnerable bridges subjected to multiple hazards	Dong et al. [50]	Earthquake Engineering and Structural Dynamics	2013
2	125	Behavior of corrosion damaged circular reinforced concrete columns under cyclic loading	Ma et al. [51]	Construction and Building Materials	2012
3	120	Life-cycle reliability of RC bridge piers under seismic and airborne chloride hazards	Akiyma et al. [32]	Earthquake Engineering and Structural Dynamics	2011
4	112	Nonlinear stress-strain behaviour of corrosion-damaged reinforcement bars including inelastic buckling	Kashani et al. [52]	Engineering Structures	2013
5	86	Seismic response and fragility of deteriorated reinforced concrete bridges	Simon et al. [29]	Journal of Structural Engineering	2010
6	77	Lifetime seismic performance of concrete bridges exposed to corrosion	Biondinia et al.[53]	Structure and Infrastructure Engineering,	2014
7	71	Nonlinear cyclic response of corrosion-damaged reinforcement bars with the effect of buckling	Kashani et al. [54]	Construction and Building Materials	2013

8	54	Probabilistic seismic loss assessment of aging bridges using a component-level cost estimation approach	Ghosh and Padgett[55]	Earthquake Engineering and Structural Dynamics	2011
9	51	Effect of steel corrosion and loss of concrete cover on strength of deteriorated RC columns	Tapan and Aboutaha [9]	Construction and Building Materials	2011
10	44	Experimental research on hysteretic behaviors of corroded reinforced concrete columns with different maximum amounts of corrosion of rebar	Yang et al. [56]	Construction and Building Materials	2016

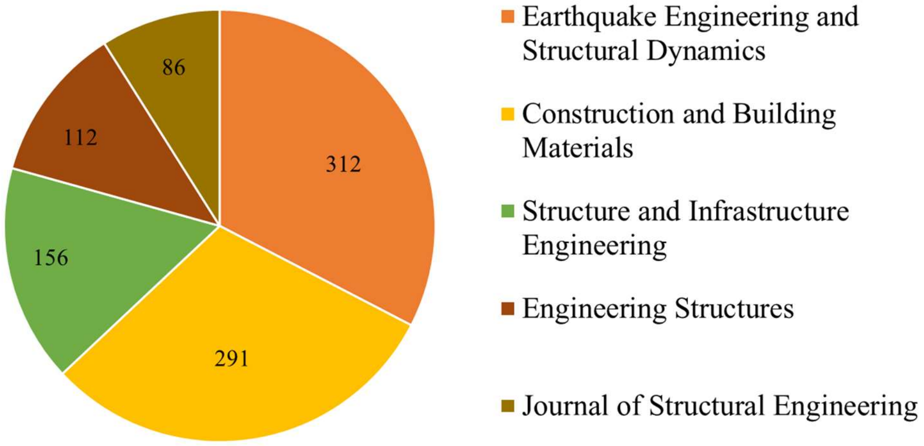


Fig. 5 Distribution of the most cited articles over journals

4. Significant findings on seismic damage assessment of corroded RC bridges

This paper classified all available literature along different perspectives on seismic damage assessment of corroded RC bridges over the last decade. Findings of these classifications enable us to identify research gaps and develop future research opportunities. Relevant information from the included articles was classified into two main categories including: experimental and numerical studies. A summary of significant findings will be presented in the following.

4.1. Experimental study on seismic responses of corroded RC bridges

Table 3 lists the experimental studies including shaking table and cyclic tests on RC bridge components over the last ten years. Although several researchers conducted experimental tests to investigate the effects of corrosion on the structural behavior of RC members, a limited number of studies have been devoted to examine experimentally the joint consideration of corrosion mechanisms and seismic/cyclic loading on the performance of RC bridge components. As presented in Table 3, the existing experimental studies limited to reverse pseudo-cyclic loading tests [40, 51, 52, 54, 56, 57-64, 66] and to the best of authors' knowledge, solely one article [65] focused on the shaking table tests of corroded RC bridge components over the last decade. Most of the articles have evaluated the effects of different corrosion degrees on seismic responses of RC components [40, 51, 52, 54, 57, 58, 59, 60, 63, 64, 65]. Some have investigated the effect of pitting and non-uniform corrosion under cyclic loads [62, 64].

In two studies, the strain-stress and buckling behavior of corroded reinforcement bars have been examined under axial, compressive and cyclic loadings [52, 54].

Table. 3 Summary of previous experimental studies on seismic damage assessment of corroded RC bridges

Authors	**Number of Specimens**	**Tested Component**	**Corrosion Level (%)**	**Loading Protocol**	**Size of Specimen**
Ma et al. [51]	13	Column	0-15.1	Cyclic	260×260× 1000mm
Kashani et al. [52]	6	RC member	6.5-25	Tension, Cyclic	200×150× 500mm, 200×250× 700mm
Kashani et al. [54]	4	RC member	6.5-25	Cyclic	250×250× 700mm
Ou et al. [57]	9	Beam	0, 12,21, 45	Cyclic	300×500× 1850mm
Ou and Chen [58]	7	Beam	0,3,6,12, 16, 35	Cyclic	300×500× 700mm
Meda [59]	4	Column	0,10,15,20	Cyclic	D=155mm L=1500mm
Yu et al. [60]	3	Beam	0-50	Tension-cyclic	150×280× 3000mm
Li et al. [61]	11	Column	10	Cyclic, Low-fatigue	250×250× 1250mm
Yuan et al. [62]	8	Column	0-10	Axial - Cyclic	300×300× 1100mm
Yang et al. [56]	5	Column	0-5,10, 15, 20	Cyclic	210×210× 1000mm
Yuan et al. [63]	6	Column	4.6,8.7,17.6,28.5,30.71,51.66,55.42	Cyclic	D=400mm L=3200mm
Yuan et al. [64]	5	Column	5, 15,20, 25	Cyclic	540×540× 2300mm
Yuan et al. [65]	4	Column	N/A	Shaking table	200×200× 1600mm
Li et al. [40]	6	Column	0,10,20	Pseudo-dynamic	300×300× 1370mm
Wang et al. [66]	5	Beam	N/A	Cyclic	150×150× 2100mm

4.1.1. RC beams

Ou et al. [57] conducted experimental tests on large-scale RC beams with four levels of corrosion through various duration including 12.5, 25, 50, and 150 days. The specimens were subjected to displacement-control cycling loadings with an increasing drift level to estimate their strength and stiffness degradation. The results indicated that the increase in the corrosion duration changed the failure mode of the beams from flexural failure, which was started by buckling of the longitudinal reinforcement, to flexural-shear failure that caused by fracture of the hoops. In another study, Ou and Chen [58] carried out experimental tests on seismic behavior of RC beams considering only transverse reinforcement exposed to corrosion. The beam specimens were designed in accordance with ACI 318 code [67] and subjected to six levels of corrosion in the potential plastic hinge region. The cyclic loads were applied with different amplitudes including drift ratio of 0.25, 0.375, 0.5, 0.75, 1.0, and 1.5. The results indicated that the RC beams could sustain 6% corrosion-sectional loss due to corrosion providing ductile behavior and after that, the increase in the corrosion level may shift the failure mode from flexural failure, corresponding to crushing the core concrete, to flexural-shear failure that was correlated to the diagonal tension cracking. Yu et al. [60]

examined experimentally the ductility, ultimate capacity, failure mode, and cross-sectional loss of two RC beams corroded by wetting–drying in a chloride environment. It was found that about 1% cross-sectional loss on tensile bars was correlated to 1% reduction in the yield and ultimate capacity of the beams. Moreover, it was reported that the impact of corrosion on the ductility of the beams was a function of the initial ductility of reinforcement. Recently, Wang et al. [66] carried out a series of experimental tests on prismatic RC beams to determine fatigue life and to examine the effects of corrosion incorporating to cyclic loadings on the seismic response of the beams. In this experimental program, specimen C-0, considered as a reference beam with no corrosion, was tested under static loads to determine the ultimate load carrying capacity of the beam and specimens C-1, C-2 and C-3 with varied corrosion degrees were subjected to cyclic loadings. It was concluded that corrosion of reinforcement bars may reduce the service life of the beams up to 60% and accelerated the deflection growth and cracking propagation in corroded RC beams subjected to cyclic loading compared to the un-corroded beams.

Fig. 6 compares the effect of cross-sectional loss on the normalized yield capacity of RC beams regarding three experimental studies [57, 58, 60]. As observed the increase in the cross-sectional loss may decrease the yield capacity of RC beams. At initial step, the yield strength of RC beams exhibits a slight reduction, whereas the increase in corrosion degree accelerates the reduction in the yield capacity of RC beams. According to Fig. 6, the yield capacity of RC beams may exhibit up to 40% decrease for a corrosion level of 45% [60].

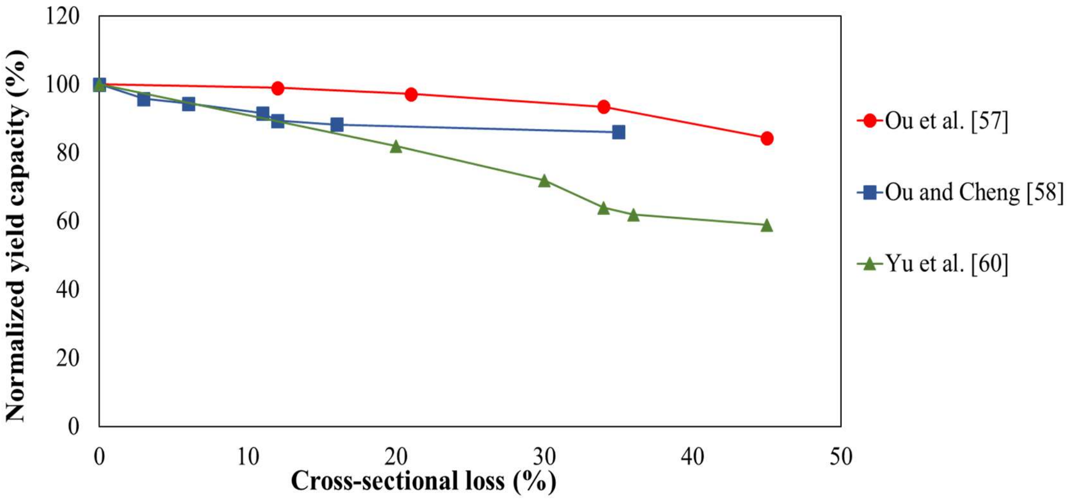


Fig. 6 Normalized yield capacity of RC beams at different level of cross-sectional loss. The data obtained from relevant research articles presented in Table 3.

4.1.2. RC columns

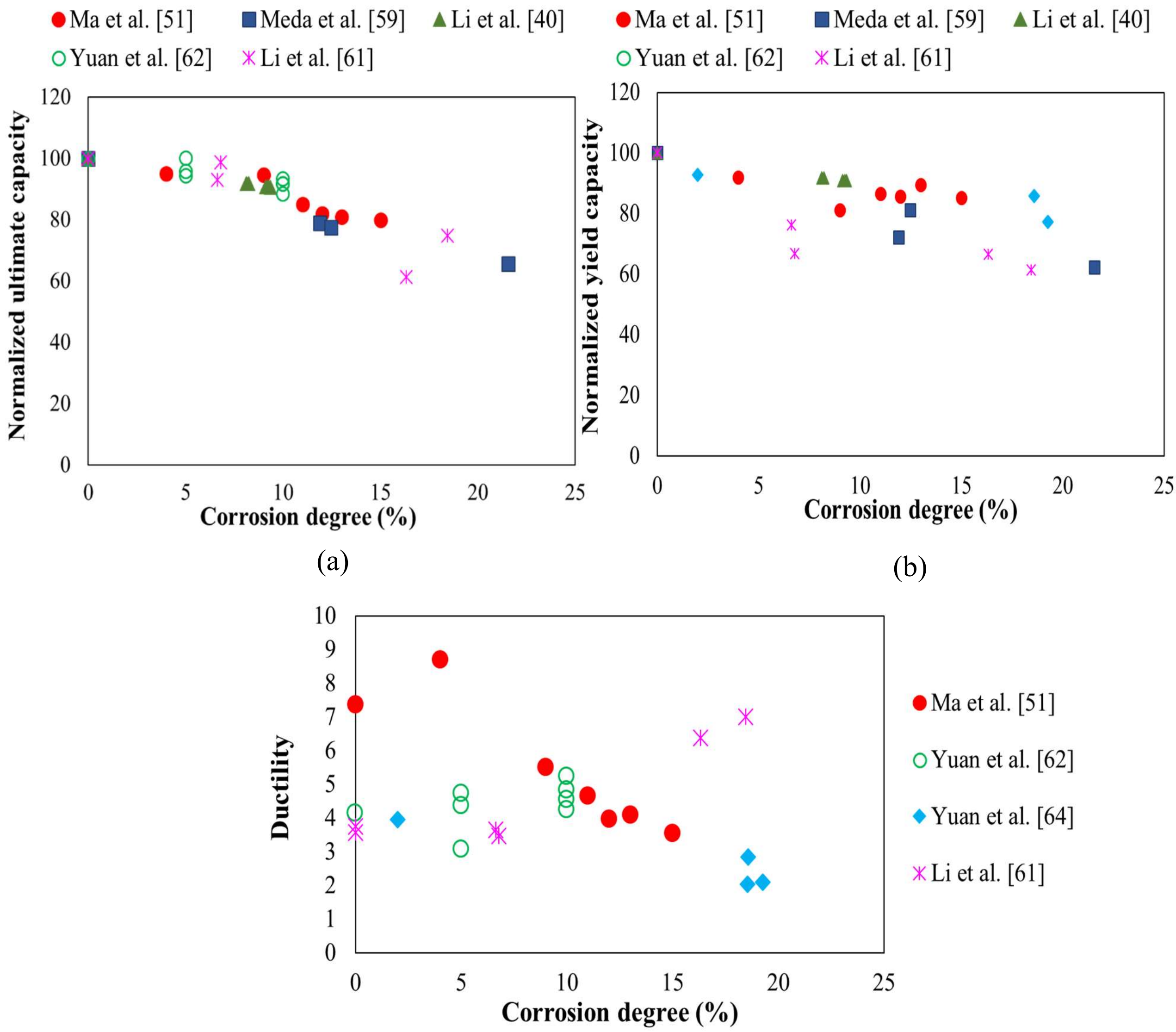
Nine of the included articles presented experimental studies on seismic performance of corroded RC columns [40, 51, 56, 59, 61, 62, 63, 64]. Several found that corrosion of reinforcement bars decreased the strength, ductility, low-cycle fatigue life, and energy dissipation capacity of RC columns under cyclic loads [51, 61, 62, 63, 64, 65].

Some explained these results by means of damage indices [59, 61]. Li et al. [61] utilized a damage index proposed by Park and Ang [68] to predict seismic damage to RC columns and compared the results to the experimental observations. It was suggested to establish further studies for seismic damage prediction of the corroded columns based on the structural damage indices. Meda et al. [59] defined a damage index as the non-dimensional energy dissipated in each cycle for all tested columns with respect to the experiment results. It was reported that the damage index remained approximately constant at damage value of 0.5 up to drift ratio of 1.5%, and then the damage measure reached 5.8 at drift ratio of 2.5%. The results also indicated that corrosion of reinforcement bars might lead to 30% reduction in the ultimate force and 50% reduction in the ultimate displacement of RC columns subjected to cyclic loadings.

Two articles have studied the effects of the non-uniform corrosion on the seismic damage of RC bridge piers [40, 64]. Among those, Li et al. [40] evaluated the impact of non-uniform corrosion of reinforcement using two failure criteria including unilateral failure and bilateral failure criteria and reported that the non-uniform corrosion caused considerable change in the post-peak behavior in the positive and negative loading directions. It was also concluded that the unilateral criterion provided more realistic results for seismic behavior of the corroded columns, whereas the results were overestimated using the bilateral failure criterion. Yuan et al. [64] conducted a series of biaxial/uniaxial pseudo-static cyclic tests on corroded RC bridge piers with non-uniform corrosion using an electrochemistry corrosion method. The results indicated that the RC piers subjected to the uniaxial loading exhibited better seismic responses compared to those subjected to the biaxial loading.

In many studies, it was found that corrosion of reinforcement bars reduced the yield and ultimate strength of RC columns under cyclic loadings [51, 56, 59, 61, 62, 63, 65]. It was reported that a 20% reduction in the mass loss of reinforcement bars could reduce the yield and ultimate capacity about 40% and 30%, respectively [59]. Ma et al. [51] conducted a set of experimental studies and developed two expressions for defining the yield and ultimate loads of the corroded columns as functions of the corrosion loss ratio and the yield and ultimate loads of the un-corroded columns, respectively. Yuan et al. [62] found that the yield strength and load carrying capacity of RC columns were strongly influenced by their corrosion degree, whereas the vertical axial loading exhibited no significant effect on the yield strength and ultimate capacity of the columns. Yang et al. [56] reported that the increase in the maximum amount of corrosion caused a considerable decrease in the flexural strength and circular stiffness of the corroded RC columns. Moreover, it was reported that as the numbers of loading cycles increased the circular stiffness of the corroded columns showed a significant decrease.

Only one research article, by Yuan et al. [65], conducted a series of shaking table tests on corroded RC bridge piers. The pier specimens with different degrees of corrosion were subjected to a series of gradually increasing ground motions. In addition, finite element models of RC columns were also developed to determine their possible failure modes during their service life. The results represented that corrosion-induced damage to stirrups was more severe than the longitudinal reinforcement bars under the ground motion excitations and consequently, the reduction in the shear capacity of the bridge piers was more significant compared to their flexural capacity. It was also reported that higher degree of corrosion enhanced the natural period and damping ratio of the RC bridge piers. Fig. 7 compares the impact of corrosion degree on the normalized ultimate capacity, normalized yield capacity and ductility of RC columns reported in the experiment studies. It is found from Fig. 7 (a) that the influence of corrosion degree in the ultimate capacity of RC columns varies from 4.1% decrease up to 34.25%. However, the effect of corrosion degree seems to be accelerated after reaching the degree of 10%. According to Fig. 7 (b) the reduction in the yield capacity of RC columns was estimated to be about 40% for a corrosion degree of 20% [59, 61]. In addition, from Fig. 7(a) and (b), it is found that at lower corrosion degrees, the yield capacity of RC columns shows greater reduction than the ultimate capacity, which reveals that the impact of low corrosion degree on the effect of yield capacity is more pronounced. However, high corrosion degrees have a significant influence on the ultimate capacity of RC columns. As observed in Fig. 7(c), the corrosion of reinforcement bars increases the ductility of RC columns when the corrosion degree is about 5%. This is due to the increase in the deformation capacity of the corroded bars, but at higher corrosion degrees, the longitudinal bars fracture and spalling of cover concrete may decrease the ductility of RC columns.



(a) (b)

(c)

Fig. 7 (a) normalized ultimate capacity, (b) yield capacity and (c) ductility of RC columns at different corrosion degrees. The data obtained from relevant research articles presented in Table 3.

4.2. Numerical study on joint impact of corrosion and seismic loads on responses of RC bridges

Table 4 lists all the included articles on numerical seismic damage assessment of corroded RC bridges with a focus on the damage parameters used in each study. The results of reviewing articles reveals that the current research is dominated by the probabilistic methods and most investigations have focused on developing time-dependent fragility models for damage assessment of RC bridges exposed to corrosion at system and component levels [28, 45, 49, 52, 68-94]. The key findings of all the included articles are summarized below.

Table. 4 Summary of previous numerical studies on seismic responses of corroded RC bridges

Authors	**Bridge Component**	**Corrosion Type**	**Corrosion Level (%)**	**Damage Parameter**
Simon et al. [29]	Columns	N/A	N/A	Drift
Ghosh and Padgett [69]	Columns, Bearings	Uniform	0-60	Curvature ductility, Displacement
Ghosh and Padgett [70]	Columns, Bearings, Abutments	N/A	0-20	Curvature ductility, Deformation
Gardoni and Rosowsky [71]	Columns	Uniform	N/A	Ductility, Drift
Dong et al. [50]	Columns	Uniform	N/A	Ductility
Biondini et al. [51]	Beam	Uniform	0-42	Displacement
Chiu et al. [72]	Columns	Uniform	N/A	Park-Ang [68] damage index
Guo et al. [73]	Columns, Bearings	Uniform	0-10	Curvature ductility, Deformation
Guo et al. [74]	Columns	Uniform	0-50	Ductility, Displacement
Ghosh and Sood [2]	Columns	Pitting	0-20	Curvature ductility, Displacement ductility
Ni Choine et al. [75]	Columns	Pitting	N/A	Ductility
Thanapol et al. [76]	Columns	Pitting	3,6, 12, 15	Displacement ductility
Rao et al. [77]	Columns	Uniform	0,5.1, 9.4, 14.7	Drift
Dizaj et al. [78]	Columns	Pitting	0-27	Displacement ductility
Deng et al. [79]	Columns	Uniform	0,14.4,33.5,50,64.4	Ductility
Cui et al. [80]	Columns	Pitting	N/A	Ductility
Yanweerasak et al. [81]	Columns	Uniform	0-4	Displacement
Cheng et al. [82]	Columns	Uniform	4-15	Drift
Liang et al. [83]	Columns, Bearings, Abutments	Uniform	N/A	Displacement ductility, Relative displacement, Displacement
Shuai et al. [84]	Columns, Bearings	Uniform	N/A	Displacement ductility, Displacement
Vishwanath and Benerjee [85]	Columns, Bearings, Abutments	Uniform	N/A	Curvature ductility, Deformation
Panchireddi and Ghosh [86]	Columns	Uniform	N/A	Park-Ang [68] damage index
Li et al.[87]	Columns, Bearings, Abutments	Pitting	N/A	Curvature, Displacement
Li et al.[88]	Columns, Bearings	Pitting	N/A	Curvature, Deformation/strain
Cui et al. [89]	Columns	Uniform	N/A	Curvature
Li et al. [90]	Columns	Pitting	N/A	Curvature ductility, Displacement ductility
Pang et al. [91]	Columns	Uniform	N/A	Drift
Xu et al. [92]	Columns	Uniform	3.9,6.8,15.5	Drift
Capacci and Biondini [93]	Columns	Uniform	N/A	Drift
Dizaj and Kashani [46]	Columns	Pitting	0,10,15,20	Mergos and Kappos [98] damage index Curvature shear strain rotation
Cheng et al. [94]	Columns	Pitting	N/A	Drift

4.2.1. Bridge piers

Thirty one of the included articles reported seismic responses of corroded RC bridge piers. Among those, nineteen research articles considered the effects of the uniform corrosion of reinforcement bars on seismic behavior of RC bridge piers [50, 53, 69, 71, 72, 73, 74, 77, 79, 81, 82, 83, 84, 85, 86, 89, 91, 92, 93]. Corrosion degradation of reinforcement bars causes uniform reduction in their cross-sectional area incorporating to form localized corrosion pits along the length of the bars. However, severe localized corrosion across multiple location along the reinforcement bars may lead to deep pits [2]. Ten articles have reported that the pitting corrosion exhibited more severe effects on seismic performance of RC bridge components compared to the uniform corrosion [2, 46, 77, 76, 77, 78, 80, 87, 88,90]. Some studies found that cross-sectional loss of reinforcement due to corrosion lead to a significant decrease in the load-carrying capacity [71, 82, 83, 89, 91, 92, 93, 94, 95, 100] and yield curvature [63, 75] of RC columns. A 16.6% reduction in the yield curvature and 21% reduction in the yield moment were reported for the 50 years corroded RC columns [82].

Some studies reported that probability of extensive/collapse damage states of corroded RC bridge piers was approximately equal to un-corroded piers under small PGAs of earthquake and the effects of corrosion could be ignored, whereas under large PGA values, the damage probability of RC piers exposed to corrosion, showed a significant increase compared to un-corroded ones at various damage levels [71, 72, 73, 82, 99, 100]. It was found that in addition to reducing the cross-sectional area, the pitting corrosion might lead to localized strain along the rebar under seismic loadings and consequently intensify the reduction in the ductility of RC components. Studies by Ghosh and Sood [2] showed that the damage limit states of RC columns exposed to the pitting corrosion followed a generalized extreme value distribution particularly at the end of the bridge service life, whereas in the uniformly corroded columns these limits exhibited lognormal distribution.

Due to the complexity of modeling pitting and non-uniform corrosion, seven of the included articles developed fragility curves for RC bridges at system and component levels considering the effects of pitting corrosion in RC columns [2, 46, 75, 76, 78, 89, 90]. It was reported that pitting corrosion caused up to 36% decrease in the yield strength of RC columns during a 100-year service life of a bridge [2]. It was also concluded that in general, damage limit states of RC columns under pitting corrosion were higher compared to those subjected to the uniform corrosion at a specific time. Moreover, non-uniform corrosion could change damage potential position and failure probability of RC columns. Failure probability of RC columns due to uniform and pitting corrosion was almost equal over the 50 years of service life. However, after 50 years, the difference between the failure probabilities of RC columns differed significantly for uniform and pitting corrosion and the results provided by the uniform corrosion were underestimated [2, 46, 87, 88,90, 96, 97, 99].

Fig. 8 compares the influence of corrosion degrees on three seismic failure modes of RC columns regarding the numerical analysis. As observed in Fig. 8(a), the increase in the corrosion degree of the reinforcement bars may shift the three failure modes, including the yielding of steel bars, cover concrete crushing and bar fracture, from higher to lower drift ratios. On the other hand, according to Fig. 8 (a), at higher corrosion degrees the concrete crushing and bar facture may occur at lower drift ratios. In addition, Fig. 8 (b) indicates that the corrosion of reinforcement bars may lead to decrease in the lateral load carrying capacity of RC columns particularly at higher corrosion degrees.

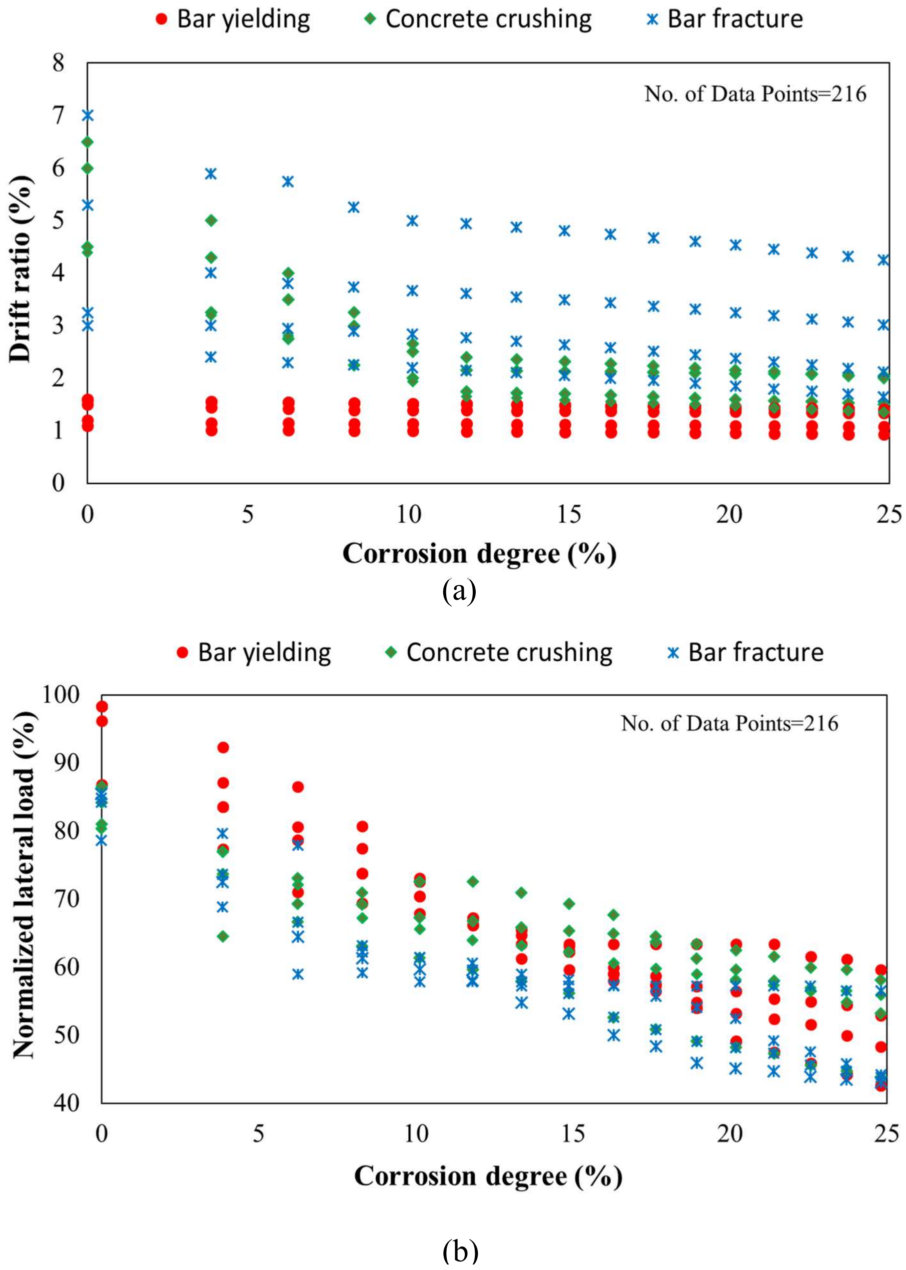
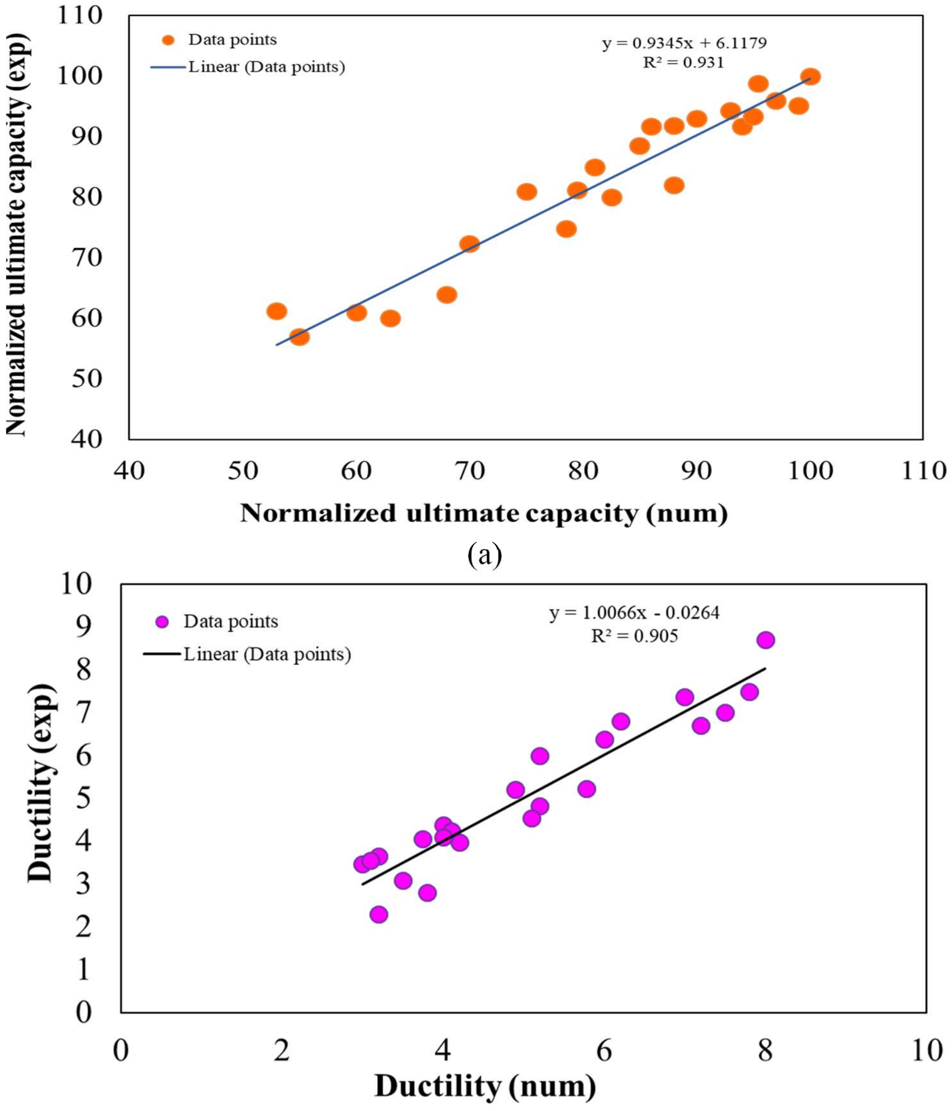


Fig. 8 (a) Drift ratio and (b) Normalized lateral load capacity of RC columns at different corrosion degrees (mass loss). The data obtained from relevant research articles presented in Table 4.

The normalized ultimate capacity and ductility of RC columns through experimental and numerical studies are compared in Fig. 9. As seen there is a good correlation between the numerical and experiment values, which confirms that the numerical analyses provide reasonable values for seismic responses of RC columns exposed to corrosion. Moreover, the correlation between numerical and experimental results shows that the finite element models are capable of simulating seismic behavior of corroded RC bridges at different corrosion degrees.



(a)

(b)

Fig. 9 Comparison of experimental and numerical results of RC piers (a) Normalized ultimate capacity and (b) Ductility at different corrosion degrees (mass loss).

4.2.2. Bridge bearings and abutments

Corrosion deterioration mechanism of elastomeric bearings may have severe impact on the lateral responses of RC bridges under earthquake excitements [93]. During earthquake, bearing anchor bolts provide a weak link to transform lateral forces from the superstructure to the substructures [101]. Chloride-induce damage and accumulation of excessive corrosion products may lead to locked bearings and corrosion of anchor bolts may change the seismic performance of the bridge bearings under seismic loadings. Six of the included articles developed time-dependent fragility curves for RC bridge systems subjected to corrosion considering damage probability of elastomeric bearings [69, 70, 73, 83, 74, 85]. It was reported that corrosion reduced the cross-sectional area of the anchor bolts that leaded to decrease in the stiffness and ultimate lateral strength of fixed bearings [73, 83, 84, 85]. However, similar trend was reported for the expansion bearings in the transverse direction in a study by Ghosh and Padgett [70], whereas it was observed that in longitudinal direction, the coefficient of friction increased and consequently the stiffness of bearings enhanced. It was also found that accumulation of corrosion debris increased the coefficient of friction in the expansion bearings that resulted in 19% and 21% reduction in the yield strength and longitudinal displacement, respectively. Moreover, it was concluded that the decrease in the ultimate strength of the expansion bearings in the transverse direction could cause 18% increase in the peak deformation. Only three of the included articles considered the corrosion of abutments in time-dependent fragility analysis at component damage level [70, 83, 85]. These articles solely evaluated the impact of corrosion in the bridge bearings in time-variant passive deformation of the abutments over the service life of bridges. It was found that the decrease in the longitudinal displacement of elastomeric bearings due to corrosion decreased the passive deformation of the abutments up to 27% [70].

4.2.3. Damage parameters used in numerical analysis

As provided in Table 4, the existing literature have mostly used simple structural parameters such as displacement or ductility to describe the damage limit states of RC bridge components and a limited numbers of studies have employed damage indices for seismic assessment of corroded RC bridges. Most of the included articles considered the curvature and displacement ductility of the columns to determine damage limit states for seismic damage analysis of bridges [2, 50 ,69, 70, 71, 73, 74, 75, 76, 79, 80, 83, 84, 85, 87, 88, 90]. Many used the drift ratio as the structural damage parameter to define the damage limit states for bridge columns [29, 71, 77, 82, 91, 92, 93, 94]. Solely three research articles including Chiu et al. [72], Panchireddi and Ghosh [86] and Dizaj and Kashani [46] defined damage limits for RC bridge columns using a damage index. Chiu et al. [72] and Panchireddi and Ghosh [86] utilized the damage index previously proposed by the Park and Ang [68] for RC members. The park and Ang [68] damage model estimates damage as a linear function of the ductility and the cumulative hysteretic energy demand. Moreover, Dizaj and Kashani [46] developed a damage index proposed by Mergos and Kappos [98] to consider the contribution of deformation mechanisms including flexural, shear, and slippage of reinforcement for seismic damage assessment of corroded RC piers. In addition, according to Table 4, deformation is the dominant damage parameter that has been used for bridge components such as elastomeric and steel bearings and bridge abutments [69, 70, 73, 83, 84, 85, 87, 88].

5. Research gap identified and need for future research

As described above, many experimental and numerical studies have been devoted to seismic damage assessment of corroded RC bridges. However, the authors' review shows that there is noticeably small numbers of research articles with a focus on using quantitative damage indices for damage estimation of RC bridges subjected to corrosion at component and system levels. On the other hand, to achieve a reliable seismic damage estimation of RC bridge exposed to corrosion, it is required to determine quantitatively the level of corrosion and seismic-induced damages to components and the overall bridge system. However, only three articles were identified in this review that utilized damage indices for damage evaluation of corroded RC bridges subjected to earthquake excitements. Moreover, the above mentioned articles solely considered damage indices for bridge columns, whereas the cumulative damages of a bridge system strongly depend on the inelastic behavior of the columns incorporating to other components such as its bearings. In addition, all previous seismic damage assessment studies on corroded RC bridges have focused on the corrosion degrees and their effects on the structural performance of RC bridges under seismic loadings, and much less attention has been paid to the damage parameters, which has been used for describing the level of induced damage due to simultaneous effects of corrosion and seismic excitements in a quantifiable degree. Whereas, choosing a reasonable damage parameter that can provide reliable damage measures for the bridge system and its components and define the level of damage under the joint impact of corrosion and seismic hazards, is of great importance in the probabilistic and deterministic seismic damage analysis of corroded RC bridges and directly affects the results. In other words, during earthquakes, bridges are subjected to many inelastic loading cycles with large displacements where the cumulative effects of repeated loading cycles must be considered in the damage estimation of bridges. Therefore, using single structural parameters such as ductility, deformation and displacement for damage evaluation of RC bridges exposed to corrosion, may overestimate the damage and provide unrealistic damage levels. Note that the only cumulative damage index has been used in the included articles, the Park and Ang [68] damage model, suffers many disadvantages and complexities, which makes difficulty in damage calculation particularly in the absence of the experimental data [90]. This highlights the fact that there is a lack of study on utilizing a practical cumulative damage index for seismic damage evaluation of RC bridge system and components exposed to different levels of corrosion. However, limitations of using reliable damage indices lead the researchers to more focus on the simple structural damage parameters and ignoring the cumulative effects of repeated loading cycles of earthquakes. Therefore, it is required to assess seismic damage of RC bridges subjected to corrosion using a reliable damage index, which can take into account the cumulative effects of pinching, stiffness degradation, inelastic deformation, and low-cycle fatigue and material nonlinearities at each step throughout the loading history during earthquakes. Currently, research on seismic damage assessment studies of bridges tend to apply damage indices on the bridge system and component levels by defining new damage models or using existing indices [90-95]. According to the above discussion, it seems necessary to implement a damage assessment methodology based on quantitative damage indices in seismic evaluation of RC bridges exposed to corrosion that is able of considering the joint impact of corrosion and cumulative effects of seismic loadings with a more reliable approach. While the current research studies have mostly focused on the probabilistic analyses of various RC bridge classes considering the damage levels based on simple structural parameters, recently the researchers have started to define and use damage indices for seismic vulnerability analyses of bridge system and components to achieve more realistic and reliable damage levels [102-108]. Damage indices are single structural parameters or combination of different structural parameters, which have been defined as a conventional approach to quantify the level of damage in a structure caused by earthquake ground motions [102, 107, 108]. It is found from the included article that corrosion has a significant influence on seismic damage states of RC bridges. On the other hand, none of the reviewed studies has been devoted to quantify the damage measure of bridge system and components under the joint consideration of corrosion and seismic loads to provide quantitative seismic performance levels for corroded RC bridges [46, 69-100, 105].

6. Conclusions

This paper presented an overview of 84 articles on seismic damage assessment of RC bridges exposed to corrosion published between 2010 and 2020 categorizing along various dimensions. Existing research gap and needs for future research were outlined. It is found that the current research tends to focus on the corrosion degree and its effects on single structural responses of RC bridges rather than conducting a damage analysis that quantifies the damage levels of RC bridges considering the joint impact of corrosion and cumulative effects of seismic loadings. In other words, the cumulative effects of repeated loading cycles including pinching, stiffness degradation, inelastic deformation, and low-cycle fatigue and material nonlinearities at each step throughout the loading history during earthquakes are major concerns that is ignored in the existing studies. Although the research trends shows that there is a growing interest in seismic damage analysis of corroded RC bridges and reveals a steep rise in the number of articles over the last three years, nevertheless, a comprehensive damage assessment methodology based on a practical and reliable cumulative damage index has not yet been presented. The main focus of these research studies was on different patterns of corrosion and reaching the accurate model for simulating its effects. The current review of literature concluded that successful implementation of seismic damage assessment of corroded RC bridges can be achieved with following concerns:

- Using a cumulative damage index for bridge components that can simulate the effects of pinching, stiffness degradation, inelastic deformation, and low-cycle fatigue and material nonlinearities at each step throughout the loading history during earthquakes for un-corroded and corroded conditions.
- Describing quantifiable damage levels that can reflect simultaneously the joint impact of corrosion degree and earthquake intensity on seismic performance of bridge components.
- Developing a comprehensive damage evaluation framework to quantify corrosion-induced damage and seismic–induced damage to a bridge system based on its components damage.
- The identified gaps and the potential opportunities for research on seismic damage assessment of RC bridges exposed to corrosion were discussed in the present paper, may be a starting point and contribute to further study on these issues

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