World Academy of Science, Engineering and Technology
International Journal of Urban and Civil Engineering
Vol:15, No:2, 2021

# Review and Classification of the Indicators and Trends Used in Bridge Performance Modeling

S. Rezaei, Z. Mirzaei, M. Khalighi, J. Bahrami

***Abstract*—**Bridges, as an essential part of road infrastructures, are affected by various deterioration mechanisms over time due to the changes in their performance. As changes in performance can have many negative impacts on society, it is essential to be able to evaluate and measure the performance of bridges throughout their life. This evaluation includes the development or the choice of the appropriate performance indicators, which, in turn, are measured based on the selection of appropriate models for the existing deterioration mechanism. The purpose of this article is a statistical study of indicators and deterioration mechanisms of bridges in order to discover further research capacities in bridges performance assessment. For this purpose, some of the most common indicators of bridge performance, including reliability, risk, vulnerability, robustness, and resilience, were selected. The researches performed on each index based on the desired deterioration mechanisms and hazards were comprehensively reviewed. In addition, the formulation of the indicators and their relationship with each other were studied. The research conducted on the mentioned indicators were classified from the point of view of deterministic or probabilistic method, the level of study (element level, object level, etc.), and the type of hazard and the deterioration mechanism of interest. For each of the indicators, a number of challenges and recommendations were presented according to the review of previous studies.

***Keywords*—**Bridge, deterioration mechanism, lifecycle, performance indicator.

Open Science Index, Urban and Civil Engineering Vol:15, No:2, 2021 publications.waset.org/10011866.pdf

## I. INTRODUCTION

THE performance of bridges are affected after entering the service phase due to various deterioration mechanisms such as aging, corrosion, fatigue and events such as earthquake, fire, explosion and more. The decline in the performance of bridges includes economic consequences such as costs of reconstruction, repair, maintenance and inspection, social, environmental and political consequences. All of these consequences are considered a major threat to the sustainability of modern society. According to this issue, evaluating the performance of deteriorating bridges is essential. The American Society of Structural Engineers (SEI)/ASCE to improve guidelines and books on the design and safety and performance evaluation of structures, in 2013, by a survey of 607,380 bridges in the United States reported that the average of life span of bridges was only 42 years [1]. These statistics point to the importance and necessity of accurate modeling of deterioration mechanisms and selection of appropriate indicators to evaluate the performance of bridges. For this reason, many efforts have been made in the past decades to evaluate the performance of these infrastructures. This study aims to review previous research on deteriorated structure and infrastructure system performance modeling over their life cycle with emphasis on bridges. In fact, the purpose of this article is to highlight the existing research weaknesses and highlight possible research potentials in modeling bridge performance. In this regard, after the review of performance indicators, the deterioration mechanisms and type of hazard considered in previous studies has been be categorized. Also, the studied indicators and the deterioration mechanisms have been compared. In this paper, the authors attempt to perform a statistical investigation on the most important performance indicators used for the evaluation of bridges with regard to the type of deterioration mechanisms affecting the performance of bridge systems. The present article provides an overview of works done in the field of bridge performance modeling. It aims to clarify the research capacity by reviewing the studies carried out on the development of performance indicators and categorizing the most common performance modeling concepts and models.

The article includes the following sections: The second section reviews the deterioration mechanisms and potential hazards for bridges. In the third section, the performance indicators of bridges are reviewed with respect to the concept and structure of the models of the indicators developed. The fourth section deals with classifying and comparing performance indicators of bridges in the presence of deterioration mechanisms. This section attempts to study the relationship between indicators. Finally, according to the statistical study of the performance indicators and deterioration mechanisms in previous literatures, suggestions were made for further study especially about those less researched.

## II. THE DETERIORATION MECHANISMS

Right after entering into the service phase, bridge performance starts to change due to various mechanisms which could mainly be classified into two main groups (according to Fig. 1). The first group includes mechanisms that gradually reduce the performance of a bridge over time. Mechanisms such as aging, corrosion and fatigue fall into this category. The second group includes mechanisms that suddenly decrease the bridge performance. Examples include natural hazards such as flood, storm, earthquake and man-

S. Rezaei is with the Department of Civil Engineering, University of Kurdistan, Sanandaj, Iran (corresponding author, phone: 0098-9390926671; e-mail: saharrezaie2012@ yahoo.com).

Z. Mirzaei is with the Jenny Planing AG, Zurich, Switzerland (e-mail: mirzaei@gmx.ch).

M. Khalighi and J. Bahrami are with the Department of Civil Engineering, University of Kurdistan, Sanandaj, Iran (e-mail: m.khalighi@uok.ac.ir, jbahrami@uok.ac.ir).

made hazards such as explosion, fire and terrorist attacks.

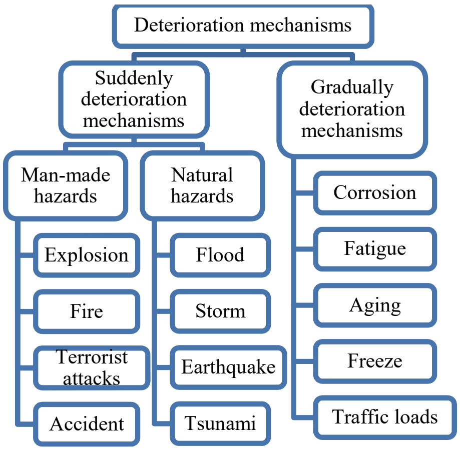

Fig. 1 Deterioration mechanisms and hazards

## III. PERFORMANCE INDICATORS

In recent decades, due to the importance and special place of bridges in road networks, researchers and infrastructure managers have come up with verities of indicators to evaluate the performance of these systems. One of the most important applications of these indicators is to provide optimal work programs for their maintenance. Many of these indicators are based on quantitative evaluation of structural safety.

In the following an overview of several performance indicators is done, as shown in Fig. 2, in the field of structure and infrastructure with special emphasis on bridges.

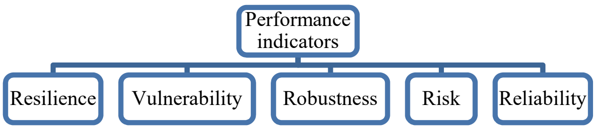

Fig. 2 Studied performance indicators

### *A. Reliability*

#### 1. General Terms and Literature

One of the key and common indicators in the field of infrastructure management is the Structural Reliability Index which is one of the most widely used indicators in assessing the performance of structures and infrastructure systems, especially bridges. This index has played an important role in the formation of many other indicators in the field of performance evaluation of infrastructure systems. In reliability theory, the safe condition is defined as a condition in which the failure of the investigated element/system does not occur or at least the probability of failure over the investigated time period is low enough that can be tolerated by the infrastructure manager. The failure of the element or system is related to two parameters of resistance (R) and load effect (S). As long as the resistance level exceeds the load effect, safe condition for the element or system is confirmed. This safe condition is shown in Reliability Theory by the limit state function (g):

$$g=R-S \tag{1}$$

According to (1), the probability of failure of an element is defined as:

$$P_{f(element)}=P(g<0) \tag{2}$$

$P_{f(element)}$ is the probability of failure of an element. Similarly, the probability of failure of a system can also be calculated. A structural system can have multiple failure modes and according to each failure mode have a limit state function. Accordingly, a system will fail when at least one of the limit state functions is violated:

$$P_{f(system)}=P(g_i<0) \tag{3}$$

where, $i$ is the number of system failure modes and $g_i$ is the system limit state function with respect to failure mode $i$. According to (2) and (3), the probability of element or system survival ($P_S$) can be written as:

$$\begin{gathered} P_{s(element)}=1-P_{f(element)} \\ P_{s(system)}=1-P_{f(system)} \end{gathered} \tag{4}$$

Assuming a Gaussian distribution of limit state functions, the reliability index for the element or system will be expressed as:

$$\beta=-\Phi^{-1}(P_f) \tag{5}$$

In (5), $\beta$ is the reliability index and $P_f$ is the probability of failure of a member or system. Also $\Phi$ is a standard normal cumulative distribution function.

There are various approaches to calculate the reliability of structures. To calculate the reliability of a system, the system failure can be modeled as a series or parallel or series-parallel combination of element limit states. Also by using appropriate assumptions about the interactions between elements of a structure, the reliability of the entire structural system can be evaluated. In general, the available methods to calculate the reliability of the structural system are in accordance with Fig. 3 [2]-[17]. Enright and Frangopol in 1999-2000 used the failure path method to assess the reliability of a general (i.e., series-parallel) system and for this purpose developed the computer program RELYSYS [18]-[20]. The RELSYS computer program is also presented by Estes and Frangopol in 1998 [21]. Tabsh and Nowak investigated the failure probability of highway bridges beams using reliability theory [22]. Reliability can quantitatively consider the load and resistance model of structural members, also by reliability method the deterioration process will also be considered as a negative effect on structural safety. Corrosion is one of the most important causes of deterioration in bridges. Therefore, the reliability of bridges can be evaluated considering this deterioration phenomenon [23]-[26]. Also, the reliability assessment due to bridge piers scour has been investigated

[27], [28]. In addition to the deterioration process, in many cases natural hazards such as earthquakes, floods, storms, etc. can endanger structure and infrastructure systems safety. For this reason, in the last two decades, researchers have evaluated the bridges reliability, respect to hazards such as earthquakes and storms [29]-[32].

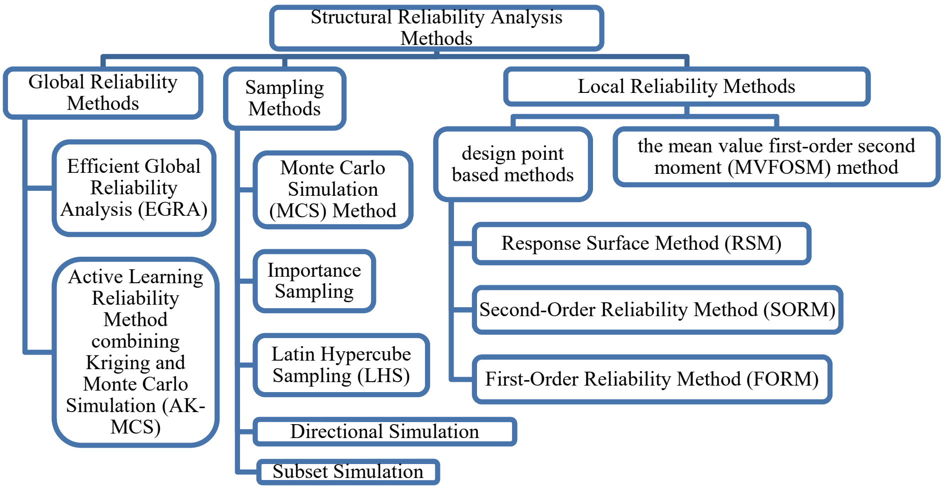

Fig. 3 Structural reliability analysis methods

In some cases, the reliability assessment of bridges has been subject to multiple hazards [33]. A comprehensive review of reliability-based performance indicators for structural members was presented by Ghosn et al. [34].

### 2. Challenges and Shortcomings

Most of the studies mentioned in the previous section focused on evaluating reliability in the presence of natural hazards. The study of the reliability of bridges under man-made hazards such as terrorist attacks, fires, etc. can be a basis for further studies in this field. In most of the recent studies, corrosion is considered as one of the most important deterioration mechanisms in the lifecycle performance modeling of concrete and steel bridges. However as shown in Fig. 4, there are many other chemical, physical and mechanical processes which cause a bridge's structural members to deteriorate over time [35]. These deterioration processes could be considered as research capacities in the reliability assessment of bridges. Generally, in the reliability assessment, limit state functions according to the load and resistance of members are needed. Research can be done to increase the accuracy of calculating the reliability of members and structural systems by providing more accurate load and resistance models.

## *B. Risk*

### 1. General Terms and Literature

In the performance assessment of structure and infrastructure systems, risk has become an increasingly important performance indicator. In general, form risk is calculated as the multiplication of the probability of failure and the consequences of failure [36].

$$\text{RISK}=P_f\times C \tag{6}$$

where, $P_f$ is the probability of element or system failure and C is the consequences of failure. The consequences of element or object failure can be divided into two parts: direct and indirect consequences. The direct consequences are related to local elements failure and only include the commercial loss aspect. For example, the cost required to replace the damaged element/object fall into this category. On the other hand, indirect consequences are associated with subsequent object failure. These consequences include several loss aspects, such as commercial loss (Secondary system reconstruction cost), safety loss and environmental loss [36].

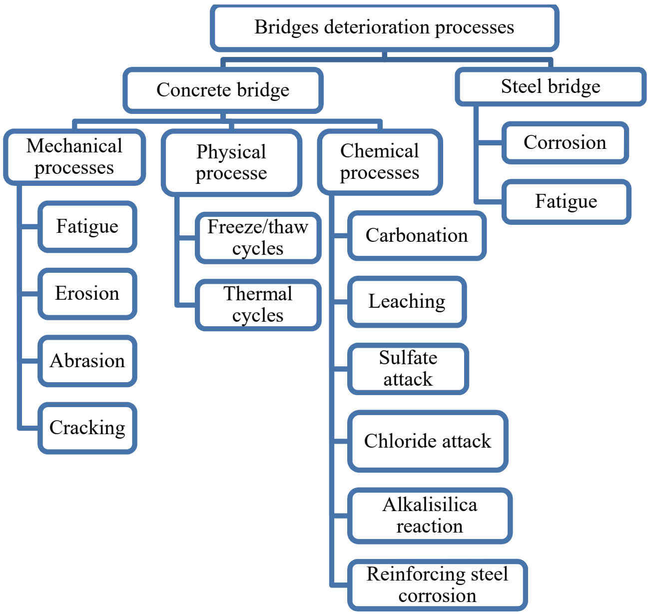

Fig. 4 Types of deterioration mechanisms in bridges

Over the past three decades, extensive studies have been conducted on risk index assessment, many of which focused on the risk assessment of bridges. Cesare et al. assessed the total risk of a bridge based on the reliability and the consequences of its closure [37]. Stein et al. used risk concepts for prioritizing scour-vulnerable bridges [38]. The consequences considered in this study are rebuild cost, running costs and time loss cost. Adey et al. assessed the risk of bridges in light of traffic and flood hazard scenarios [39]. Lounis developed a multi-criteria approach to bridge structural assessment with respect to the concept of risk [40]. Similarly, Stein and Sedmera proposed an approach for risk-based management of bridges. The proposed method is based on the absence of foundation information [41]. Ang investigated a risk-based decision-making by considering life-cycle considerations to civil infrastructure design [42]. Deco and Frangopol presented a rational framework for quantifying the risk of highway bridges under multiple hazards. The hazards considered in this study were environmental attacks, scouring, abnormal traffic loads and earthquakes [43]. Zhu and Frangopol investigated the effects of the deterioration in structural resistance, the type of system modeling (series or parallel or series-parallel) and the correlations among the failure modes of elements on the time-dependent risk of the structural systems during their life cycle [36]. Saydam et al. presented a methodology for quantifying the risk of the bridge superstructures with respect to expected direct and indirect losses related to the bending failure of girders [44]. In recent years, researchers studied the assessment of the risk index with respect to seismic events [45]-[47]. According to studies carried out, risk index can be useful and efficient in structures and infrastructures performance assessment, especially bridges considering the importance of their existence on the road network. In addition, this index can provide a more comprehensive view of the system performance considering the consequences of element or object failure. The results of the risk assessment can be used in any decision making regarding the optimal maintenance plan for structure and infrastructure systems, especially bridges.

### 2. Challenges and Shortcomings

As mentioned in the previous section, the risk index is calculated as the multiplication of the probability of failure and the consequences of failure. Many models have been proposed to calculate the different consequences of bridge failure [36]-[47]. Most of these models are related to maintenance and user costs. In order to improve the risk assessment of bridges, more advanced models can be proposed in such a way that accurately assesses the environmental consequences of failure. A review of studies on bridge risk indexes shows that there is research capacity to study this index in the presence of man-made hazards such as explosion, accident, etc.

## C. Robustness

### 1. General Terms and Literature

Robustness is generally referred to as the ability of a structure to resist progressive collapse under sudden local damage. This index is one of the key measures in the field of progressive collapse and damage tolerant structures [48]. Generally, this indicator is important under extreme events such as accident, explosions, and abnormal loads, etc. that can suddenly reduce the performance of a structure or infrastructure system. Although robustness has been recognized as a key indicator in the science of structural engineering, there is no widely accepted measure for this indicator. Over the past decades, many studies have been conducted on robustness index and its calculation methods that the following will be explained. In general, the proposed methods for calculating the robustness index can be divided into five main groups as shown in Fig. 5 [49]-[51].

### 2. Risk-Based Models

Baker et al. proposed a risk-based robustness index. Their index is expressed as ratio of direct risk to the total risk [52]:

$$I_{\mathrm{Rob}}=\frac{R_{Dir}}{R_{Dir}+R_{Ind}} \tag{7}$$

$R_{Dir}$ is the direct risk and $R_{Iir}$ is the indirect risk.

### 3. Reliability-Based Models

Frangopol and Curley proposed a reliability-based robustness index. The proposed index based on the concept of structural system redundancy [53].

$$I_{\mathrm{Rob}}=\frac{\beta_{intact}}{\beta_{intact}+\beta_{damaged}} \tag{8}$$

where, $\beta_{intact}$ is the reliability index of the intact system and $\beta_{damaged}$ is the reliability index of the damaged system. In a similar manner, Maes et al. proposed a measure of structural robustness which is expressed as a ratio of failure probability of the undamaged system to the failure probability of the damaged system [54].

$$I_{\mathrm{Rob}}=\min_i \frac{P_{fo}}{P_{fi}} \tag{9}$$

where, $P_{fo}$ is the failure probability of the intact system and $P_{fi}$ is the failure probability of the damaged system (assuming one impaired member $i$).

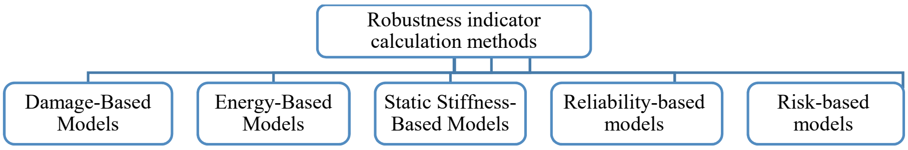

Fig. 5 Robustness indicator calculation methods

#### 4. Static Stiffness-Based Models

In general, the stiffness of structure and infrastructure systems decreases after extreme events. Accordingly, Starossek and Haberland proposed a stiffness-based measure of robustness ($I_{\mathrm{Rob}}$). This measure is expressed as a ratio of stiffness matrix of the damaged system to the stiffness matrix of the undamaged system [49].

$$I_{\mathrm{Rob}} = \min_j \frac{\det K_j}{\det K_O} \tag{10}$$

$K_O$ is the system stiffness matrix of the intact structure and $K_j$ is the system stiffness matrix of the damaged structure (after removing a structural element or a connection $j$).

#### 5. Energy-Based Models

Starossek and Haberland proposed an energy-based measure of robustness. This measure is based on the comparison of the energy released during an initial failure and the energy required for the failure development [49].

$$I_{\mathrm{Rob}} = 1 - \max_j \frac{E_{r,j}}{E_{f,k}} \tag{11}$$

where, $E_{r,j}$ is the energy released during the initial failure of a structural element j that can lead to damaging structural element k, and $E_{f,k}$ is the energy required for the failure of the structural element k.

#### 6. Damage-Based Models

Starossek and Haberland proposed a damage-based measure of robustness. This measure is based on the quantification of the damage progression resulting from initial damage [49].

$$I_{\mathrm{Rob}} = 1 - \frac{P}{P_{lim}} \tag{12}$$

$P$ is the maximum total damage resulting from a certain initial damage and $P_{lim}$ is the acceptable total damage.

One of the important researches related to the concept of robustness has been done by Maes et al. [54]. In this research, the basic aspects of infrastructure systems robustness assessment are also expressed. Further studies on the assessment of the robustness indicator will be discussed in the next section. These studies can be divided into two general categories. The first category is associated to the investigation of this index in the presence of extreme events. In other words, in these researches, the robustness index is considered as the ability of a system to resist damage caused by an extreme event [48], [55]-[57]. In the second category of the studies, the robustness index with respect to deterioration phenomenon and with special emphasis on corrosion is investigated.

Saydam and Frangopol presented a framework for assessment of the structure robustness index. In this study, the effect of live load increase and corrosion is investigated on this indicator [48]. Also, due to the importance of corrosion in reinforced concrete bridges, the robustness indicators for these infrastructures were studied in the presence of this deterioration mechanism [58]-[60].

Wisniewski et al. presented an approach for load capacity evaluation of existing railway bridges based on robustness quantification [61]. Recently a comprehensive review of robustness and resilience of structures under extreme loads is provided by Stochino et al. [62]. This review article can be of great help to researchers in this field.

#### 7. Challenges and Shortcomings

As mentioned earlier, robustness is generally referred to as the ability of a structure to resist progressive collapse under sudden local damages. However, in some studies, such as Baker et al., robustness is proposed as a risk-based index [52]. Since part of the risk calculation is related to the consequences of failure, providing accurate models for calculating the consequences of progressive collapse is difficult, and therefore studies on these models can be the basis of further research in this field.

### *D. Vulnerability*

#### 1. General Terms and Literature

The performance of structural and infrastructural systems, including bridges, decreases after entering the service phase due to extreme natural or man-made events. The vulnerability index is one of the important indicators in the quantitative assessment of the sensitivity of an element or structural system to such events. Also, vulnerability is defined as the key measures used to capture the essential features of damage tolerant structures. Lind proposed a probabilistic measure of Vulnerability ($I_{\mathrm{Vul}}$). This measure is expressed as a ratio of the failure probability of the damaged system to the failure probability of the intact system [63].

$$I_{Vul} = \frac{P_f(r_d,Q)}{P_f(r_o,Q)} \tag{13}$$

where, $r_d$ is a particular damaged state, $r_o$ is an undamaged system state, $Q$ is the prospective loading, $P_f(r_d,Q)$ is the failure probability of the damaged system, and $P_f(r_O,Q)$ is the failure probability of the intact system.

Saydam and Frangopol presented a framework for the assessment of the structure vulnerability index. In this study, the effect of live load increasing and corrosion is investigated on this indicator [48]. Generally, the vulnerability indicator of bridges is investigated subject to natural hazards such as floods, hurricanes and especially earthquakes [64], [65]. For example, Morbin et al. proposed a probabilistic framework for the seismic assessment and FRP retrofitting of existing bridges [64]. As mentioned before, aging and natural deterioration mechanisms such as corrosion reduce the performance of bridges in their life cycle. Therefore, these deterioration mechanisms should also be considered when assessing the vulnerability of bridges. Accordingly, some research on the seismic vulnerability of existing bridges has examined in the presence of environmental deterioration [66]-[69].

#### 2. Challenges and Shortcomings

Most studies about the assessment of vulnerability index in bridges refer to seismic events [64], [65]. According to these studies, environmental deterioration is one of the factors affecting the seismic vulnerability of bridges. Therefore, upgrading models for deterioration mechanisms such as corrosion can provide research capacity in the field of seismic vulnerability assessment of bridges. Also, the vulnerability assessment of bridges can be investigated under multiple hazards such as explosions, accidents, and abnormal loads, etc.

### *E. Resilience*

#### 1. General Terms and Literature

Webster's Unabridged Dictionary has defined resilience as "the ability to bounce or spring back into shape, position, etc., after being pressed or stretched" [70]. Generally, the resilience of systems is investigated subject to extreme events. Bruneau et al. considered resilience as the ability of infrastructures to resist the effects of extreme events and the ability of the system to recover original functionality after such events [70]. They presented a model to evaluate the resilient of infrastructures against seismic loads such as earthquake. In their model, the resilience indicator ($I_{Res}$) can be defined as the integral of the triangle in Fig. 6:

$$\text{Res}=\int_{t_0}^{t_1}(100-Q(t))\mathrm{d}t \tag{14}$$

$t_0$ is the time occurring of extreme events, $t_1$ is time at full recovery and $Q$ is the percentage functionality of the system.

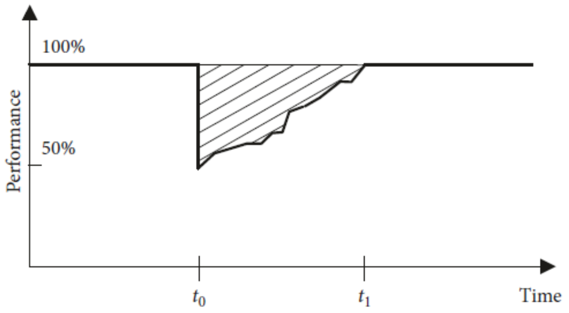

Fig. 6 Resilience triangle [70]

Renschler et al. improved this model and proposed $I_{Res}$ to be defined as [71]:

$$I_{Res}=\int_{t_0}^{t_0+T_{LC}}\frac{Q(t)}{T_{LC}}\mathrm{d}t \tag{15}$$

where $T_{LC}$ stands for control time.

Based on the Faber model, the time-dependent resiliency index ($I_{Res}$) of infrastructure systems can be calculated as [72]:

$$I_{Res}(t)=E_X\frac{B_1(X,t)}{B_0(X)} \tag{16}$$

where $t$ is the time after the occurrence of an extreme event. $B_0$ and $B_1$ are the benefits of a system before and after the event, respectively. The expectation $E_X$ is taken over all relevant uncertainties $X$ influencing the benefits of the system.

Lounis and McAllister presented a framework for risk-informed decision making for infrastructure systems. The suggested framework considered the resilience of an infrastructure system as its capacity to resist hazards, minimize functionality reductions, and reduce recovery times and costs [73]. The effects of functionality and recovery time on system resilience are shown as in Fig. 7.

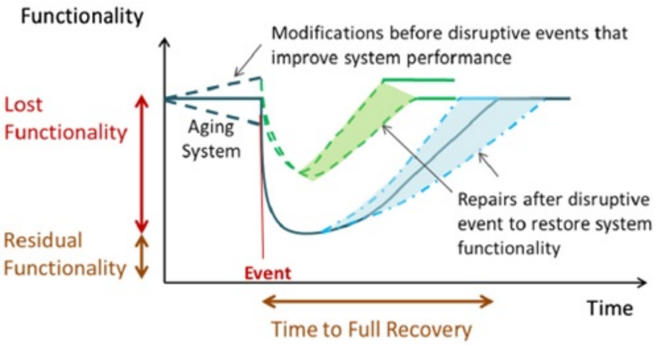

Fig. 7 Effects of functionality and recovery time on system resilience [70], [74]

In general, the resilience index of infrastructure systems is assessed under seismic events [70], [73]-[77]. Aging and environmental attacks can also affect seismic performance and functionality. Therefore, a lifecycle approach should be adopted to evaluate the seismic resilience of structures [78].

#### 2. Challenges and Shortcomings

As mentioned earlier, problems such as aging and environmental deterioration can also affect seismic performance and functionality. Therefore, a lifecycle approach should be adopted to evaluate the seismic resilience of structures.

As shown in Fig. 7, the concepts of functionality and recovery time are important in the resilience assessment of infrastructure systems. Recovery time after the occurrence of extreme events depends on many factors. One of these factors is the extent of damage of other infrastructure systems that support the recovery process [73]. Therefore, evaluating the resilience of infrastructure systems such as bridges at the network level of infrastructures under various damage scenarios can provide the basis for more studies.

## IV. CLASSIFICATION AND COMPARISON OF PERFORMANCE INDICATORS

### *A. Assessment of Relationship between Performance Indicators*

Previous sections reviewed the equations and studies of bridge performance indicators, including those of reliability, risk, robustness, vulnerability and resilience. This section assesses the relationship between the mentioned performance indicators. We assume that an infrastructure system, such as a bridge, is under hazard H and local damage D. In such a condition, if the performance target is to prevent the system collapse (system reliability), the probability of infrastructure system collapse can be expressed as [79]:

$$P(F)=P(F|D).P(D|H).P(H) \tag{17}$$

where P (H) is the probability of occurrence of hazard H, P (D|H) is the conditional probability of local failure D given the occurrence of H, P (F|D) is the probability of infrastructure system collapse given the occurrence of local damage D, and P (F) is the probability of infrastructure system collapse given the occurrence of local damage D and hazard H. This equation shows that reliability is expressed in terms of robustness and vulnerability indicators. So that P (F|D) is related to system robustness and P (D|H) is associated with the vulnerability of system members. Therefore, it can be concluded that the reliability index is more complete and comprehensive than those two indicators. In other words, one can say that robustness and vulnerability indicators are the subset of the reliability concept. On the other hand, according to (6), it is seen that the essential parameters to calculate the risk index, are the probability of system failure and the consequences of failure. For convenience, this equation is repeated below. Given this equation, one can easily conclude that reliability is one of the most important pillars in the risk assessment process.

Regarding the relationship between the resilience index and other indices, one can point to the research conducted by Lounis and McAllister [73]. In this research, reliability and risk indicators are important elements in highway deck resilience assessment. According to this study, the resilience index can be considered as one of the most comprehensive indices at the object level and includes other indicators.

### *B. Classification of Performance Indicators in Presence of Different Deterioration Mechanisms*

In this section, all indicators were classified according to Table I from three different aspects. There are many uncertainties in the process of structural safety assessment. Therefore, most of the available relationships for evaluating performance indicators are presented in probabilistic form and only in a few cases, the robustness and resilience indexes have been formulated in deterministic form. This demonstrates that the mastery and application of probabilistic concepts are essential in the process of evaluating the performance of structures and infrastructures. On the other hand, studies on each of the indicators can be assessed at a particular level of structure such as cross-section, element, system or network. Table I shows that most of the indicators have been considered at the object level. As mentioned above, the performance of bridges is reduced due to various reasons including deterioration (corrosion and fatigue) and hazards such as earthquakes, floods, storms, explosions and increased traffic loads over the lifecycle of the structure.

TABLE I
CLASSIFICATION OF RESEARCH CONDUCTED ON PERFORMANCE INDICATORS

| Performance Indicator | Reliability | Risk | Robustness | Vulnerability | Resilience |
|---|---|---|---|---|---|
| Approach | | | | | |
| Probabilistic | ✓ | ✓ | ✓ | ✓ | ✓ |
| Deterministic | | | ✓ | | ✓ |
| Level | | | | | |
| Element Level | ✓ | | | | |
| Object Level | ✓ | ✓ | ✓ | ✓ | ✓ |
| Network Level | | ✓ | | | ✓ |
| Hazard | | | | | |
| Earthquakes | ✓ | ✓ | | ✓ | ✓ |
| Flood | ✓ | ✓ | | | |
| Hurricanes | ✓ | | | | |
| Aging and progressive deterioration (Corrosion) | ✓ | ✓ | ✓ | ✓ | ✓ |
| Accidental actions | | | ✓ | | |
| Traffic loads | ✓ | ✓ | ✓ | ✓ | ✓ |

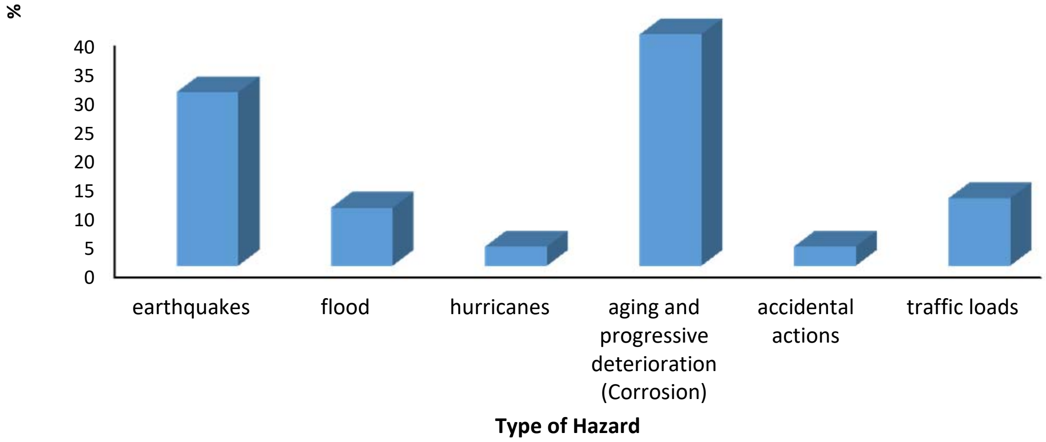

Fig. 8 Percentage of hazard type participation in past studies

Table I shows the types of hazards considered in previous researches in the area of bridge performance evaluation. The results of this classification are also shown in Fig. 8. According to the reviewed studies, most research has focused on evaluating the performance of bridges with respect to the deterioration (corrosion) process and the seismic hazard. This indicates that other hazards such as floods and storms have been less addressed. Therefore, these hazards provide a large area for further studies in this field. On the other hand, all the studies reviewed in this article are broken down by type of index, as shown in Fig. 9. It can be clearly seen that the reliability index is one of the most widely used and popular indicators in the past decades for assessing the performance of bridges. On the other hand, the number of studies focused on other indicators is comparable, suggesting the potential for research on indicators such as risk, robustness, vulnerability and resilience, is much higher.

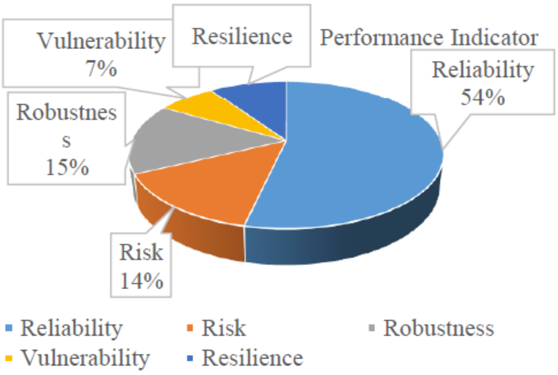

Fig. 9 Percentage of participation of type of performance indicators of bridges in past studies

## V. Conclusion and Recommendations

According to this study, the following results and suggestions are presented:

1) In recent decades, extensive studies have been conducted to evaluate the performance of bridges. In this regard, performance indicators have gradually improved and changed from deterministic to probabilistic. This indicates that researchers have incorporated the uncertainties in the performance evaluation process into computations.
2) Reliability index is one of the most used indicators in the bridge performance modeling. It plays an important role in the formation of many other performance indicators.
3) The resilience index is one of the most comprehensive indices at the object level and includes other indicators.
4) In evaluating the performance of bridges, the mechanism of corrosion deterioration and seismic hazard have been extensively investigated. The interaction of these two factors in the evaluation of bridge performance has also been of interest to researchers. However, since the decay of bridges over time is inevitable, this deterioration mechanism should be considered in assessing the performance of bridges in the presence of other natural events such as floods, storms, and so on.
5) The majority of studies corresponding to the resilience index are related to seismic hazard. Based on the review of previous studies, it is concluded that there has been less focus on determining resilience based on aging and deterioration processes. Therefore, further study in this field has immense research scope.
6) Since the risk index considers the probability of failure with its consequences, it can take a comprehensive look at the performance of a bridge. Accordingly, one can provide relationships based on the risk index in evaluating other performance indicators (such as Baker who used the risk index for evaluating the robustness indicator [53]).
7) Mainly the consequences of an element or system failure are considered as maintenance costs, user costs and so on. Attempts to accurately model these consequences can provide the basis for further study.
8) Studies evaluating the performance of bridges often focused on reinforced concrete bridges. In the United States, however, nearly 30% of bridges are made of steel material [80]. Therefore, evaluation of steel bridge performance can be the basis for further research in this field.

## References

[1] ASCE. 2013. *Report card for America's infrastructure*. Reston, VA, ⟨http://www. infrastructurereportcard.org⟩.

[2] Hendawi, S. and Frangopol, D.M. 1994. System reliability and redundancy in structural design and evaluation. *Structural Safety*, 16(1-2):47-71.

[3] Czarnecki, A.A. and Nowak. A.S. 2007. Reliability-based evaluation of steel girder bridges. In *Proceedings of the Institution of Civil Engineers-Bridge Engineering*, 160, Issue BE1: 9–15.

[4] Ditlevsen, O. and Bjerager, P. 1986. Methods of structural systems reliability. *Structural Safety*, 3(3): 195-229

[5] Galambos, T. V. 1990. Systems reliability and structural design. *Structural Safety*, 7(2-4): 101-108.

[6] Rashedi, M.R. and Moses, F. 1988. Identification of failure modes in system reliability. *Journal of Structural Engineering*, 114(2): 292-313.

[7] Tang, K. and Melchers, R.E. 1988. Incremental formulation for structural reliability analysis. *Civil Engineering Systems*, 5(3): 153-158.

[8] Thoft-Christensen, P. and Murotsu, Y. 1986. *Application of Structural Systems Reliability Theory*. , Springer, Berlin.

[9] Vu, K. and Stewart, M.G. 2000. Structural reliability of concrete bridges including improved chloride-induced corrosion models. *Structural Safety*, 22(4): 313-333.

[10] Huang, C., El Hami, A., and Radi, B. 2017. Overview of structural reliability analysis methods—Part I: local reliability methods. *Incert. Fiabil. Syst. Multiphys*, 17: 1-10.

[11] Huang, C., El Hami, A., and Radi, B. 2016. Overview of structural reliability analysis methods—Part II: sampling methods. *ISTE OpenScience: London, UK.*

[12] Huang, C., El Hami, A., and Radi, B. 2016. Overview of structural reliability analysis methods—Part III: global reliability methods. *ISTE OpenScience: London, UK.*

[13] Liu, W. D., Neuenhoffer, A., Ghosn, M., and Moses, F. 2001. *Redundancy in highway bridge substructures* (No. Project D12-47 FY'97).

[14] Ghosn, M., and Moses, F. 1998. *Redundancy in highway bridge superstructures* (Vol. 406). Transportation Research Board.

[15] Okasha, N.M. and Frangopol, D.M. 2010b. Novel approach for multi-criteria optimization of life-cycle preventive and essential maintenance of deteriorating structures. *Journal of Structural Engineering*, 136(8): 1009-1022.

[16] Okasha, N.M. and Frangopol, D.M. 2010d. Time-variant redundancy of structural systems. *Structure and Infrastructure Engineering*, 6(1-2): 279-301

[17] Yang, S., Frangopol, D.M., and Neves, L.C. 2004. Service life prediction of structural systems using lifetime functions with emphasis on bridges. *Reliability Engineering and System Safety*, 86(1): 39-51.

[18] Enright, M.P. and Frangopol, D.M. 1999a. Condition prediction of deteriorating concrete bridges. *Journal of Structural Engineering*, 125(10): 1118-1125.

[19] Enright, M.P. and Frangopol, D.M. 1999b. Reliability-based condition assessment of deteriorating concrete bridges considering load redistribution. *Structural Safety,* 21(2): 159-195.

[20] Enright, M.P. and Frangopol, D.M. 2000. RELTSYS: A computer program for life prediction of deteriorating system. *Structural Engineering and Mechanics*, 9(6): 557-568

[21] Estes, A. C., and Frangopol, D. M. 1998. RELSYS: a computer program for structural system reliability. *Structural engineering and mechanics,* 6(8): 901-919.

[22] Tabsh, S. W. and Nowak, A. S. 1991. Reliability of highway girder bridges. *Journal of structural engineering,* 117(8): 2372–2388.

[23] Val, D. V. and Melchers, R. E. 1997. Reliability of deteriorating RC slab bridges. *Journal of structural engineering,* 123(12): 1638–1644.

[24] Stewart, M. G. and Rosowsky, D. V. 1998. Structural safety and serviceability of concrete bridges subject to corrosion*. Journal of Infrastructure systems,* 4(4): 146–155.

[25] Vu, K. A. T. and Stewart, M. G. 2000. Structural reliability of concrete bridges including improved chloride-induced corrosion models. *Structural safety,* 22(4):313–333.

[26] Kong, J. S. and Frangopol, D. M. 2003. Life-cycle reliability-based maintenance cost optimization of deteriorating structures with emphasis on bridges. *Journal of Structural Engineering*, 129(6): 818–828.

[27] Johnson, P. A. and Ayyub, B. M. 1992. Assessing time-variant bridge reliability due to pier scour. *Journal of Hydraulic Engineering.* 118(6): 887–903.

[28] Muzzammil, M., Siddiqui, N. A., and Siddiqui, A. F. 2008. Reliability considerations in bridge pier scouring. *Structural Engineering and Mechanics*. 28 (1): 1–18

[29] Choi, E., DesRoches, R., and Nielson, B. 2004. Seismic fragility of typical bridges in moderate seismic zones. *Engineering Structures*, 26(2): 187–199.

[30] Duenas-Osorio, L., and Padgett, J. E. 2011. Seismic reliability assessment of bridges with user-defined system failure events. *Journal of engineering mechanics*, 137(10): 680–690.

[31] Padgett, J. E., Spiller, A., and Arnold, C. 2012. Statistical analysis of coastal bridge vulnerability based on empirical evidence from Hurricane Katrina. *Structure and infrastructure engineering*, 8(6):595–605.

[32] Ataei, N., and Padgett, J. E. 2012. Probabilistic modeling of bridge deck unseating during Hurricane events. *Journal of Bridge Engineering*, 18(4): 275-286.

[33] Yanweerasak, T., Pansuk, W., Akiyama, M., and Frangopol, D. M. 2018. Life-cycle reliability assessment of reinforced concrete bridges under multiple hazards. *Structure and Infrastructure Engineering*, 14(7), 1011-1024.

[34] Ghosn, M., Frangopol, D. M., McAllister, T. P., Shah, M., Diniz, S. M. C., Ellingwood, B. R., and Zhao, X. L. 2016. Reliability-based performance indicators for structural members. *Journal of Structural Engineering*, 142(9): F4016002.

[35] Biondini, F., and Frangopol, D. M. (2016). Life-cycle performance of deteriorating structural systems under uncertainty. Journal of Structural Engineering, 142(9), F4016001.

[36] Zhu, B., and Frangopol, D. M. 2012. Reliability, redudancy and risk as performance indicators of structural systems during their life-cycle. *Engineering Structures*, 41: 34–49.

[37] Cesare, M., Santamarina, J. C., Turkstra, C. J., and Vanmarcke, E. 1993. Risk-based bridge management. *Journal of Transportation Engineering*, *119*(5): 742-750.

[38] Stein, S.M., Young, G.K., Trent, R.E., and Pearson, D.R. 1999. Prioritizing scour vulnerable bridges using risk. *Journal of Infrastructure Systems*, *5*(3): 95-101.

[39] Adey, B., Hajdin, R. and Bruhwiler, E. 2003. Supply and demand system approach to development of bridge management strategies. *Journal of Infrastructure Systems*, 9(3): 117-131.

[40] Lounis, Z. 2004. Risk-based maintenance optimization of bridge structures. In *2nd International Colloquium on Advanced Structural Reliability Analysis Network (ASRANet)*, 1-9.

[41] Stein, S. and Sedmera, K. 2006. *Risk-based management guidelines for scour at bridges with unknown foundations*. Transportation Research Board of the National Academies.

[42] Ang, A. H–S. 2011. Life-cycle considerations in risk-informed decisions for design of civil infrastructures. *Structure and Infrastructure Engineering*, 7(1-2):3-9.

[43] Decò A. and Frangopol, D.M. 2011. Risk assessment of highway bridges under multiple hazards. *Journal of Risk Research*, *14*(9): 1057-1089.

[44] Saydam, D., Frangopol, D.M, and Dong, Y. 2013b. Assessment of Risk using Bridge Element Condition Ratings, *Journal of Infrastructure Systems*, *19*(3): 252-265.

[45] Ghosh, J., and Padgett, J. E. 2011. Probabilistic seismic loss assessment of aging bridges using a component-level cost estimation approach. *Earthquake Engineering and Structural Dynamics*, 40(15): 1743-1761.

[46] Alipour, A., and Shafei, B. 2015. Assessment of post-earthquake losses in a network of aging bridges. *Journal of Infrastructure Systems*, *22*(2):04015023.

[47] Zanini, M. A., Faleschini, F., and Pellegrino, C. 2016b. Seismic loss assessment of deteriorating bridge networks, *in 8th International Conference on Bridge Maintenance, Safety and Management IABMAS2016* (Foz do Iguacu), 26–30 June 2016.

[48] Saydam, D., and Frangopol, D. M. 2011. Time-dependent performance indicators of damaged bridge superstructures. *Engineering Structures*, 33(9): 2458–2471.

[49] Starossek, U., and Haberland, M. 2011. Approaches to measures of structural robustness. *Structure and Infrastructure Engineering*, 7(7-8): 625-631.

[50] Anitori, G., Casas, J. R., and Ghosn, M. 2013. Redundancy and robustness in the design and evaluation of bridges: European and North American perspectives. *Journal of Bridge Engineering*, 18(12):1241–1251.

[51] Cavaco, E., Casas, J. R., Neves, L., and Huespe, A. 2013. Robustness of corroded reinforced concrete structures. A structural performance approach. *Structure and Infrastructure Engineering*, *9*(1): 42-58.

[52] Baker, J.W., Schubert, M., and Faber, M. 2008. On the assessment of robustness. *Structural Safety*, 30(3): 253–267.

[53] Frangopol, D. M., and Curley, J. P. 1987. Effects of damage and redundancy on structural reliability. *Journal of structural engineering*, 113(7): 1533-1549.

[54] Maes, M. A., Fritzsons, K. E., and Glowienka, S. 2006. Structural robustness in the light of risk and consequence analysis. *Structural engineering international*, 16(2): 101-107.

[55] Ghosn, M., and Moses, F. 1998. *Redundancy in Highway Bridge Superstructures* (Vol. 406). Transportation Research Board.

[56] Liu, W. D., Ghosn, M., Moses, F., and Neuenhoffer, A. 2000. *Redundancy in Highway Bridge Substructures*, NCHRP Report 458, Washington, DC: Transportation Research Board.

[57] Sorensen, J. D., Rizzuto, E., Narasimhan, H., and Faber, M. H. 2012. Robustness: theoretical framework. *Structural engineering international*, 22(1): 66-72.

[58] Biondini, F., and Frangopol, D. M. 2014. Time-variant performance indicators for concrete bridges exposed to corrosion. *In 9th Austroads Bridge Conference* (pp. 1-13). Australian Road Research Board (ARRB).

[59] Cavaco, E., Neves, L., and Casas, J. R. 2017. Reliability-based approach to the robustness of corroded RC structures. *Structural Concrete*, 18(2): 316-325.

[60] Cavaco, E., Neves, L., and Casas, J. R. 2018. On the robustness to corrosion in the life-cycle assessment of an existing reinforced concrete bridge. *Structure and Infrastructure Engineering*, 14(2): 137-150.

[61] Wisniewski, D., Casas, J. R., and Ghosn, M. 2006. Load capacity evaluation of existing railway bridges based on robustness quantification. *Structural Engineering International*, 16(2): 161-166.

[62] Stochino, F., Bedon, C., Sagaseta, J., and Honfi, D. 2019. Robustness and Resilience of Structures under Extreme Loads. *Advances in Civil Engineering, 2019.*

[63] Lind, N. C. 1995. A measure of vulnerability and damage tolerance. *Reliability Engineering and System Safety*, *48*(1), 1-6.

[64] Morbin, R., Zanini, M. A., Pellegrino, C., Zhang, H., and Modena, C. 2015. A probabilistic strategy for seismic assessment and FRP retrofitting of existing bridges. *Bulletin of earthquake Engineering*, 13(8): 2411-2428.

[65] Zampieri, P., Zanini, M. A., and Faleschini, F. 2016. Derivation of analytical seismic fragility functions for common masonry bridge types: methodology and application to real cases. *Engineering failure analysis*, 68: 275-291.

[66] Choe, D., Gardoni, P., Rosowsky, D., and Haukaas, T. 2009. Seismic fragility estimates for reinforced concrete bridges subject to corrosion. *Structural Safety*, 31(4): 275-283.

[67] Ghosh, J., and Padgett, J. E. 2010. Aging considerations in the development of time-dependent seismic fragility curves. *Journal of Structural Engineering*, 136(12): 1497-1511.

[68] Simon, J., Bracci, J. M., and Gardoni, P. 2010. Seismic response and fragility of deteriorated reinforced concrete bridges. *Journal of*

*Structural Engineering*, 136(10): 1273-1281.

[69] Zanini, M. A., Pellegrino, C., Morbin, R., and Modena, C. 2013. Seismic vulnerability of bridges in transport networks subjected to environmental deterioration. *Bulletin of Earthquake Engineering*, 11(2): 561-579.

[70] Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., ... and Von Winterfeldt, D. 2003. A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake spectra*, 19(4):733-752.

[71] Renschler, C. S., Frazier, A. E., Arendt, L. A., Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. 2010. *A framework for defining and measuring resilience at the community scale: The PEOPLES resilience framework* (pp. 10-0006). Buffalo: MCEER.

[72] Faber, M. H. 2015, October. Codified risk informed decision making for structures. In *Proceedings of the symposium on reliability of engineering systems (SRES2015). Hangzhou, China* (pp. 15-17).

[73] Lounis, Z., and McAllister, T. P. 2016. Risk-based decision making for sustainable and resilient infrastructure systems. Journal of Structural Engineering, 142(9): F4016005.

[74] McDaniels, T., Chang, S., Cole, D., Mikawoz, J., and Longstaff, H. 2008. Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation. *Global Environmental Change*, 18(2): 310-318.

[75] Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. 2010. Framework for analytical quantification of disaster resilience. *Engineering structures*, 32(11): 3639-3649.

[76] Zobel, C. W. 2011. Representing perceived tradeoffs in defining disaster resilience. *Decision Support Systems*, 50(2): 394-403.

[77] Bocchini, P., Frangopol, D. M., Ummenhofer, T., and Zinke, T. 2013. Resilience and sustainability of civil infrastructure: toward a unified approach. *Journal of Infrastructure Systems*, 20(2): 04014004.

[78] Biondini, F., Camnasio, E., and Titi, A. (2015). "Seismic resilience of concrete structures under corrosion." Earthquake Eng. Struct. Dyn. 44(14), 2445–2466.

[79] Ellingwood, B.R. 2005. Risk-informed condition assessment of civil infrastructure: State of practice and research issues. *Structure and infrastructure engineering*, 1(1): 7-18.

[80] FHWA. 2015. *Highway bridges by superstructure material 2015*. Washington, DC, ⟨http://www.fhwa.dot.gov/bridge/n bi/no10/ma)