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A State-of-the-Art Review of Bending and Shear Behaviors of Corrosion-Damaged Reinforced Concrete Beams

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A State-of-the-Art Review of Bending and Shear Behaviors of Corrosion-Damaged Reinforced Concrete Beams

by Mahmoodreza Soltani, Amir Safiey, and Almarie Brennan

Steel corrosion is mainly at fault for the trend of deterioration among U.S. infrastructure—namely, bridges, pipelines, and wharves. Reinforced concrete (RC) is used as the primary construc- tion material worldwide. Reinforcement corrosion can significantly impair mechanical properties of RC members, including shear and bending capacities. In the past decades, several attempts have been made to investigate the impacts of corrosion on the mechanical behavior of RC members. It can be observed that the number of research programs conducted on this topic has rapidly increased in recent years. Therefore, there is a need in the body of knowledge to encapsulate the relevant findings in the form of a state-of-the-art review. This paper presents a chronological literature review of investigations on different components of mechanical behavior of RC beams (including shear and flexural strengths) under corrosion. The most significant contributions of these studies are identified and presented. This study presents simple relationships that rely on the current literature to be used by practitioners and designers for quick evaluation of RC beams in corrosion distress.

Keywords: bond (concrete-to-reinforcement); deterioration; flexural capacity; residual strength; shear capacity.

INTRODUCTION

The American Society of Civil Engineers (ASCE) recently published its 2017 Report Card (ASCE's 2017 Infrastructure Report Card); the national grade for U.S. infrastructure is reported as a "D+" overall and as a "C+" for the "Bridges" category. Structural deficiency of these infrastructures is one of the main contributors to such a low rating. Almost 40% of the 614,387 bridges in the United States are 50 or more years old. In 2016, 9% (56,007) of the bridges were reported "structurally deficient" (Fig. 1). Many bridges are reaching the end of their design service life, and their average age continues to increase. It was recently estimated that $123 billion is needed to rehabilitate the country's bridge backlog. Furthermore, in a similar study, the Federal Highway Administration (FHWA) estimates that more than 30% of existing bridges have already exceeded their service life (50 years mostly) and will require more maintenance and reha- bilitation in the near future (FHWA 2011).

Reinforced concrete (RC) stands out as the main construc- tion material in use worldwide and nationwide (Aïtcin 2000). Steel reinforcement corrosion can be blamed largely for the trend of deterioration of the U.S. infrastructure (for example, bridges) that also can significantly impair

al. 2007; Wood 2008). There is a lack of a codified approach to predict the remaining capacity of corroded RC members. A gap of knowledge in this field is recognized due to the dire need of engineers to evaluate mechanical behavior of RC members deteriorating by corrosion. The first step toward this goal is to gather a state-of-the-art review on the topic of shear and flexural behaviors of corrosion-damaged RC members.

In the 1950s, the deterioration of RC members was initially investigated for structures exposed to coastal condi- tions and marine environments full of chloride contents

mechanical properties of RC structures (Schmitt 2009). For instance, although many factors contributed to the complex

ACI Structural Journal, V. 116, No. 3, May 2019. MS No. S-2017-453.R4, doi: 10.14359/51714481, received June 20, 2018, and case of the 2006 "de la Concorde" Overpass failure in Laval, QC, Canada, it was detected that excessive corrosion of rein- forcement was one of the main causes of failure (Johnson et

Fig. 1—Corrosion-damaged RC members (photo courtesy of H. Layssi, used with permission).

(Halstead 1955; Lewis and Copenhagen 1959; Stratfull 1957; Wakeman et al. 1958; Gewertz 1958; Tremper et al. 1958). The destructive effects of these severe environmental conditions on steel reinforcement result in the decommis- sioning of RC infrastructures—for example, Dickson Bridge in Montreal, QC, Canada (Palsson and Mirza 2002). In almost all RC structures located in this type of environment, significant deteriorations can be observed before reaching the end of their expected life cycle (Palsson and Mirza 2002; Shayanfar et al. 2007).

While in the past 60 years there have been many research programs focused on the evaluation, repair, and rehabilitation of corrosion-damaged RC members, there has been an increase in investigations on the mechanical behavior of these members within the last decade. Due to the national importance of this critical safety issue, this study seeks to elucidate shear and flexural behavior reviews of the current state of knowledge discussing RC beams in the presence of corrosion. The results of this study are relevant for researchers, designers, and practitioners active in the field of concrete structural engineering.

The objective of this study is to present a comprehensive historical literature review on the influences of corrosion on the mechanical behavior of reinforced concrete beams, comprised of proposals from 1955 to 2017—approximately 60 years of research. This state-of-the-art review seeks to provide a cate- gorized list of investigations conducted on components of mechanical behavior of RC beams (flexure and shear) and show how these studies have changed over time.

RESEARCH SIGNIFICANCE In the absence of provisions to evaluate the structural performance of RC members in the major concrete design codes, such as ACI 318, the objective of this study is to facil- itate the creation of such a provision. This study aimed to gather references on which this topic has been estigated. Corrosion of reinforcement in RC structures has the in role in the structural deficiency of North America’s crum- ng infrastructure. This study seeks to elucidate a method- ical iew of the current state of knowledge discussing the shear and flexural behaviors of corrosion-damaged RC eams. The results of this study are useful for researchers, esigners, and practitioners active in this field. This collec- tion of e body of knowledge into one study can pave the way for further evelopments in codification and modeling.

LITERATURE REVIEW

tructural impacts from corrosion in concrete embers

Reinforcement is used in concrete members to ompensate for the fact that concrete is relatively weak under nsion. Because the tensile strength of concrete is negligible, all e applied longitudinal stresses at cracks pass through the steel einforcement. Bond stresses between steel reinforcing bar and rrounding concrete gradually transfer longitudinal forces from einforcement to the concrete material. Mean- while, the ‘tension iffening’ mechanism (‘tension stiffening’ is defined as the effect f concrete acting in tension between cracks on the reinforcement ress) is developed as the two materials slide on top of each other hayanfar et al. 2007).

Figure 2 shows a four-point bending test configuration, e most common testing method in this current literature study, plied on a simply supported RC beam. This procedure emonstrates the importance of the concrete-to-reinforce- ment ond and the influence of corrosion on the mechan- ical behavior f a RC beam. The mechanical behavior of RC members is ndermined in the presence of reinforcement corrosion. Two types f corrosion can affect reinforcement, including pitting (a calized form of corrosion by which cavities are produced in the aterial) and uniform (the corrosion that proceeds at the same rate ver the exposed material surface). Corrosion in RC members ads to a reduction in the cross-sectional area of longitudinal and ansversal reinforcement. This mechanism not only causes a ecrease in cross-sectional area of reinforcements but also iminishes the bond stiffening action between reinforcement and oncrete. Therefore, the flexural and shear capacities of RC beams e negatively influenced (Fig. 2) (Rodriguez et al. 1997; Castel et . 2000).

The loss of cross-sectional area and reduction of the ltimate strength also lead to the loss of ductility in RC beams. he maximum displacement of RC beams under the applied load

Fig. 2—Mechanism of corrosion-damaged RC beam.

action of longitudinal reinforcement is of the resisting mechanisms of RC beams against shear forces).

This study is focused only on conventional RC beams. The investigations of the mechanical behavior of precast concrete members, concrete columns, and concrete shear walls are not included in this study due to the shortage of adequate number of conducted research programs in the literature. There is a need for conducting more experimental and analytical research programs on these mentioned structures.

Previous literature review studies of corrosion in RC members

There are two main reasons of corrosion in concrete members: carbonation corrosion and chloride corrosion. Zhou et al. (2015) reviewed research programs investigating the mechanical properties of concrete members, including cracking and spalling of concrete, reduction in reinforcing bar cross-sectional area, loss in interfacial bond strength, prediction of concrete carbonation depth, and chloride penetration into concrete. However, this study did not evaluate the shear and flexural capacities of corroded concrete beams. Mancini and Tondolo (2014) conducted a literature review study on the bond degradation due to corrosion in reinforced concrete members. The effects on long and short embedment length specimens along with different methods of bond evaluation were reviewed in the study. Since the literature review of bond degradation effect was previously studied, this current study is focused on the other mechanical behavior of corroded concrete members, including flexural and shear behaviors.

Statistical information of this literature study

The research programs reviewed in this current study have been conducted from 1955 to 2017. The number of research programs conducted at different time intervals is shown in Fig. 4. The figure shows that more attention has been recently paid to this subject, as most research programs were conducted from 2011 to 2017 (70%). It is also observed that there is more research conducted to investigate the effects of corrosion on flexural behavior of RC beams compared to those on shear behavior.

reduced compared to a similar intact RC member (McLeish)87). The bond and anchorage failures at the end regions of RC embers are other deficiencies resulting from corroded inforcement in concrete members (Rodriguez et al. 1994). The fects of corrosion on the load-carrying capacity of RC members e summarized in Fig. 3. Hence, the state-of-the-art of the llowing components in the mechanical behavior of concrete es are discussed in this study:

- exural behavior (experimental and analytical studies); and
- Shear behavior (experimental and analytical studies).

gure 3 summarizes the mechanisms of degradation in the exural and shear strengths as results of corrosion in RC beams. C members undergo two main diminishments when corrosion curs on the reinforcement: 1) the cross-sectional area of inforcement reduces; and 2) the corrosion product occupies ore room compared to the intact steel, which leads to a radial essure on the surrounding concrete. These two mechanisms ally influence the behavior of reinforced concrete in three ays: 1) mechanical properties of concrete and steel inforcement can be impaired (for example, Palsson and Mirza 002] reported how mechanical behavior of corroded inforcement differs from the intact reinforcement); 2) the cessive radial pressure applied by corrosion products at a rtain level leads to the concrete cover spalling that causes the velopment and propagation of longitudinal cracks in RC embers; and 3) the interfacial property of concrete and steel duces as discussed by Shayanfar et al. (2007).

Deterioration of the bond between concrete and inforcement can result in a change of failure mode in RC embers (for example, from the flexural to the bond failure). exural and shear capacities of RC beams are assessed by a rfect bond assumption, which would not be an acceptable sumption for corroded steel bars. These local impairments lead global deteriorations, mainly in flexural and shear capacities. It ould be mentioned that the corrosion of longitudinal reinforcement could impair shear capacity of the concrete mainly by influencing dowel action (dowel

g. 3—Effects of corrosion on load-carrying capacity and iffness of concrete beams (after Tahershamsi [2016]).

Fig. 4—History of research programs conducted on mechanical behavior of corroded members.

toire Matériaux et Durabilité des Constructions (L.M.D.C.) in Toulouse, France (Vidal et al. 2007). The test setup is geared to simulate wet-dry cycles of corrosion by subjecting the specimen to cycles of exposure and non-exposure (Chen et al. 2017). Seven percent of tests gathered in this current study were corroded using this method. Finally, in the naturally induced corrosion method, corroded specimens from a real project (usually retired structures) are used to test for residual mechanical capacities (Tanaka et al. 2001).

In most of the experimental research programs from the literature, the specimens were corroded first (using the mentioned methods above) and then tested. However, in some cases, to simulate the natural corroding situation, the specimens were simultaneously loaded and corroded (Khan et al. 2014; Tanaka et al. 2001). Upon completion of the test, the degree of corrosion is simply measured by weighting the mass loss of reinforcements due to corrosion compared to the measured weight of intact reinforcement. In addition, some other research programs employed X-ray scanning tech- niques that enabled more precise capturing of mass loss in corroded reinforcement (Michel et al. 2011). The reinforce- ment mass loss ratio is calculated by the following equation

$C^{W\ W}$

W^{w}

Fig. 5—Distribution of conducted experimental works in the literature.

Additionally, the distribution of experimental programs conducted in the literature across the different countries shows that only 5% of the research programs have been conducted in the United States (Fig. 5). Although no solid conclusion can be derived based on the total number of research programs, this suggests the necessity of conducting more experimental research programs to investigate the effect of corrosion in concrete members that are more compatible with U.S. standards and practices.

Corroding methods for RC members

In the literature, there are three main methods to exper- imentally corrode RC members: 1) accelerated; 2) envi- ronmentally induced; and 3) natural. In the accelerated (galvanostatic) method, corrosion on the steel reinforcement is induced by applying an electrical potential using a stain- less steel bar as the cathode and the steel bar in concrete as the anode (Juarez et al. 2011; Lachemi et al. 2014). By changing the applied current density or time intervals, the corrosion level can be controlled. The degree of corrosion has a direct relationship with time and electric current inten- sity, which can be explained through Faraday's law (Mangat and Elgarf 1999b; Mancini and Tondolo 2014). A high level of corrosion within a short period of time can be achieved using this method (Yuan et al. 2007). Alonso et al. (1998) reported the acceptable maximum nominal current intensity of 100 $\mu A/cm^2$ to prevent quick and undesirable corroding. This current also causes the induced corrosion to be in the upper boundary of the corrosion value in nature (Alonso et al. 1998). This method is the most common approaches among the research programs in the body of knowledge (90% of gathered tests in this current study from the litera- ture were corroded using this method).

In the environmentally induced corrosion method, the specimens are placed inside a chamber with an artificial corroding environment to simulate the natural corrosion situation. To achieve such an environment, salty air is constantly sprayed into the chamber containing the speci- mens (for example, Vidal et al. [2007]). This method has been adopted in a long-term program conducted at Labora-

$= -$

$_{con} \quad _{cor}$

(1) $_{con}$ where W_{con} is the weight of intact (control) reinforcement before corrosion; and W_{cor} is the weight of the same rein- forcement after corrosion occurrence.

Moreover, the degree of corrosion can be assessed based on the loss of reinforcement cross-sectional area (C_A). Through an experimental study of 58 RC cylindrical members with different levels of corrosion, Shayanfar et al. (2007) reported the following empirical relationship (presented as follows with some rearrangements)

C^{A}

$= A_s - A_s$

$^{0}A_{s0} = - + +_{w} 0.2\ 0.08\ _{d}c\ 0.039\ C\ ^{d}_{c}$ (2)

where A_s and A_{s0} are the cross-sectional areas of corroded and intact (control) reinforcement, respectively; c is the concrete cover; and d is the reinforcement nominal diameter. Through this empirical equation, designers and practitioners can find the loss of reinforcement cross-sectional area (C_A) by having the mass loss ratio (C_w) and some geometrical properties of a RC member (c and d).

Experimental studies on flexural behavior

Flexural capacity can be estimated following different design codes, such as ACI 318-14, with a reasonable degree of accuracy. There should be attention paid to the fact that throughout its service life a structural component is exposed to deteriorative agents. This can impair the strength and serviceability of RC members. The degree of impairment is directly related to the durability design of RC members exposed to a specific environment. This section reviews the influence of corrosion over the longitudinal reinforcement on the overall flexural behavior of RC beams.

A comprehensive study of experimental efforts was conducted to understand the influence of longitudinal reinforcement corrosion on flexural behavior of RC beams. Table 1 summarizes the characteristics and key findings of the experimental research programs conducted in the litera- ture to investigate the flexural behavior of RC beams under corrosion. Including the results of 133 tests (133 tested specimens) from the literature, Fig. 6 presents the ratio of the flexural capacity of a test with corrosion, M_{cor}, to that of the uncorroded test (control test), M_{con}, with respect to the reinforcement mass loss, C_w, developed in longitudinal reinforcement. The average moment ratio M_{cor}/M_{con} is 0.87. The moment capacity of a corroded member is not signifi- cantly reduced for the longitudinal mass losses of less than 0.045. Table 2 shows the other statistical parameters for this moment ratio, including minimum, maximum, and coeffi- cient of variation (COV) of moment ratios.

The following equation was detected to determine the trend of the experimental data

$$M_{cor}/M_{con} = -0.17\ln(C_w) + 0.4 \quad (3)$$

A statistical procedure is needed to determine the best fitting curve to the data, which is beyond the scope of this study. According to the data distribution, the following model is proposed as a lower-bound to safely predict the flexural strength of a corroded test specimen based on the control flexural strength and the mass loss ratio

$$M_{cor}/M_{con} = -0.17\ln(C_w) + 0.15 \quad (4)$$

Equation (3) represents the average trend of corrosion influence on the flexural capacity of beams, while Eq. (4) is a more conservative representation of the trend. Ali et al. (2015) proposed a practice-oriented framework to predict the remaining flexural and shear behavior of beams with corroded reinforcements. Flexural capacity of the illustrative example worked out by these researchers with 15% longitu- dinal reinforcement mass loss is around 72.2% and 47.2% using Eq. (3) and (4), respectively. The framework proposed by Ali et al. suggests a flexural capacity reduction of 82.0%. The estimated values of flexural strength calculated by Eq. (3) and Ali et al. (2015) are less than 10% different.

Analytical studies on flexural behavior

On the other hand, some analytical models have been proposed in the literature to explain the flexural capacity of corroded RC beams. Mangat and Elgarf (1999b) proposed the following relationship through an extensive experimental program

$$B = 1 - \sin^{2} \square\square \; \square 2 \, . \, 312 \, T_D \, i \, \ln i \, \square\square \; \square \quad (5)$$

where B is the percent of flexural strength; T is the time elapsed in years after the occurrence of corrosion; D is the reinforcing bar diameter (mm); and i is the rate of corrosion (μA/cm^2).

Azad et al. (2007) provided a two-step relationship to predict the flexural capacity of RC beams. First, the flexural capacity with reduced reinforcement cross-section needs to be carried out. Then, another factor β is then as follows to modify the obtained value to calculate the bond loss

$M_{res} = \beta \cdot M_{th,c}$ (6)

where M_{res} is the moment capacity with a reduced cross section, and $M_{th,c}$ is the flexural capacity of the corroded beam considering the loss of the bond as well as the cross-sectional area. The model was modified using a set of new test results (Azad et al. 2010).

Oyado et al. (2011) provided a relationship between the ratio of maximum load bearing in corroded and uncorroded states and the degree of corrosion using regression analysis as follows

$P_{uc}/P_{un} = 1 - kC$ (7)

where P_{uc} is the ultimate bearing load of the corroded specimen; P_{un} is the ultimate bearing load of the uncorroded specimen; k is a factor estimated as 1.35; and C is the corrosion rate. Xia et al. (2012) proposed the following model

$M_{uc} = M_{u0}(1 - 1.2902\eta_{average})$ (8)

where M_{uc} is the flexural capacity of the corroded beam; $\eta_{average}$ is the average corrosion rate; and M_{u0} is the flexural capacity of the uncorroded beam. Wang et al. (2015b) provided a relationship between the cross-sectional area loss and the reduced flexural capacity based on regression analysis (separately for plain and deformed reinforcement). Dong et al. (2016) proposed the following relationship

$P_{cor} = P_{arch}(0.343\ln(T_{cor}/T_{arch}) + 0.052a/d + 0.875)$ (9)

where P_{cor} is the capacity of the corroded beam; P_{arch} is the load capacity of the unbonded beam; T_{cor} is the maximum bond force in the anchorage region of the corroded beam; T_{arch} is the maximum bond force in the anchorage region of the unbonded beam; and a/d is shear span-to-effective depth ratio.

Ting and Nowak (1991) proposed an approach, which includes the loss of cross-sectional area, to predict moment curvature of a RC section. Capozucca and Cerri (2003) proposed an analytical approach, which accounts for corrosion of reinforcing bar in the compressive zone. A critical review was conducted through three analytical methods for predicting the moment capacity of RC beams (Cairns and Zhao 1993; Eyre and Nokhasteh 1992; Rodriguez et al. 1997). Thereafter, they proposed an analytical algorithmic proce- dure to estimate the behavior of corroded beams. Wang et al. (2015b) proposed a model which takes into account compat- ibility conditions with the partial length of corrosion and the bond loss. Han et al. (2014) proposed the following relation- ship to obtain moment capacity of the corroded beam (M_n)

$M_n = C_c \square\square \square c - \beta_2 {}_1 c \square\square \square + C_s(c - d') + 0.5 T_c$

$\square\square \square h - c \square\square$

$\square 1 - \varepsilon_r \varepsilon_t$

$T d \square\square \square\square\square \square + {}_s(-c)$ (10)

Table 1—Summary of experimental programs to evaluate flexural capacity of corroded RC beams

f_c', MPa $\rho_s f_y$, MPa

No. of corroded test, No. of control test

Corroding method, μA/cm^2 Loading

steps

Test type Significant findings Reference

40.0 2.9 21, 3 Acc[*] (200) FC[†] FP[‡] Low range of reinforcement mass loss (0 to 0.045) does not
have significant influence on flexural capacity of beam.
Al-Sulaimani et al. (1990)

30.0 0.7 7, 1 Acc FC Un[§] Load-carrying capacity and ductility of slabs significantly
decrease through increase in corrosion level.
Almusallam et al. (1996)

40.4 8.2 21, 10 Acc (100) FC FP Corrosion influence on structural behavior of beams may differ
according to beam detailing.
Rodriguez et al. (1997)

40 .0 (cube) 6.3 103, 8
Acc (1000, 2000, 3000 and 4000)
FC FP Breakdown of bond between steel reinforcement and concrete due to corrosion is main source of flexural capacity reduction.
Mangat and Elgarf (1999a)

45.0 2.9 2, 2 Env[||] Sus[#] + Wet & dry
TP[**] Corrosion in longitudinal zone influences beam capacity. It
more critically diminishes ductility of beam. Castel et al. (2000)

27.0 2.5 10, 2 Acc (80) FC TP Corrosion reduces beam flexural stiffness. Torres-Acosta et
al. (2004)

40.5 5.2 8, 1 Acc (215) FC & Sus FP Corrosion impairment and external structural loading
simultaneously interacts.
El Maaddawy et al. (2005)

40.7 6.1 52, 4 Acc (250) FC FP Predictive relationship based on relatively comprehensive program was proposed using test results. test
Azad et al. (2007)

27.0 2.4 11, 1 Acc (80) FC TP Pitting was found to be main reason for moment
capacity reduction.
Torres-Acosta et al. (2007)

38.8 (cube) 4.0 10, 4 Acc (60) FC TP It was observed that corrosion increased capacity. Some
specimens are continuous spans. Cairns et al. (2008)

28.0 6.4 42, 6 Acc (1780) FC TP Previous predictive model is updated. Azad et al. (2010)

27.9 5.6 11, 2
Env & Acc (350 to 1330)
FC FP Local loss plays important role on influence of corrosion on
flexural moment capacity. Oyado et al. (2011)

30.7 (cube) 6.0 18, 2 Acc + Wet
& Dry FC FP Relationship is proposed to estimate remaining capacity of
corroded beams. Xia et al. (2012)

45.0 2.9 2, 2 Env + Wet
& Dry Sus TP Corrosion changed failure mode from shear to flexure. Zhu et al. (2013)

46.5 11.2 11, 2 Nat[††] Sus FP Discrepancies observed between naturally and accelerated
corroded tests on their structural behavior.
Tahershamsi et al. (2014)

45.0 6.0 2, 1 Env + Wet
& Dry Sus TP Bending stiffness has no meaningful relationship with degree
of corrosion. Vu et al. (2014)

45.0 2.9 1, 1 Env + Wet
& Dry Sus TP Ductile failure changed to brittle failure due to corrosion. Zhu and François
(2014)

28.0 (cube) 2.5 11, 1 Acc (1087) FC FPB Corrosion does not change failure mechanism of slabs. Kearsley and Joyce (2014)

45.0 2.9 2, 1 Env + Wet
& Dry Sus TP Corrosion can change failure mode from compression crushing
to longitudinal flexural failure. Yu et al. (2015)

45.0 2.9 2, 2 Env + Wet
& Dry Sus TP Corrosion in deep beams can change failure mode from
compression crushing to longitudinal flexural failure. Zhu et al. (2015)

37.2 4.7 14, 8 Acc (1800) FC FP
Corrosion has more influence on flexural behavior of beams reinforced with plain bars compared with those reinforced with deformed bars.
Wang et al. (2015a)

45.0 2.9 1, 1 Env + Wet
& Dry Sus TP Corrosion is more influential on ductility compared to flexural
strength of beam. Zhu et al. (2016)

27.9 13.8 15, 6 Acc FC FP Corroded beams undergoing bond failure capacity can be
predicted using arch action. Dong et al. (2016)

*Acc is accelerated corrosion applied. †FC is first corrosion induced and then tested. ‡FP is four-point bending test. §Un is uniform loading configuration. ||Env is environmentally induced corrosion. #Sus is sustained loading while corrosion is induced. **TP is three-point bending test. ††Nat is naturally induced corrosion.

value of concrete compressive strength and reduced concrete compressive strength. Feng et al. (2018) proposed a method to include corrosion effects in sectional analysis method.

In addition, nonlinear finite element analysis (NFEA) was employed to analyze corroded members with different material models (Dekoster et al. 2003; Shayanfar and Safiey 2008). Finite element analysis (FEA) was also used to study the flexural behavior of different RC beams with corroded reinforcement (Coronelli and Gambarova 2004; Kallias and Rafiq 2010; Vu et al. 2014; Jnaid and Aboutaha 2016). The corrosion-damaged RC beams were modeled to evaluate the residual flexural behavior (Jnaid and Aboutaha 2014; Potisuk et al. 2011).

Overall, the following noteworthy terms were repeatedly used in the literature to estimate the reduced flexural capacity of corrosion-damaged RC beams: reduced cross-sectional area of longitudinal reinforcement (A_s), yield strength of longitudinal reinforcement (f_y), corrosion rate (μA/cm^2), corrosion degree (%), effective depth of beam (d), shear span-to-effective depth ratio (a/d), and bond and anchorage capacities.

Experimental studies on shear behavior

Similar to longitudinal reinforcement, transversal reinforcement can be damaged in the presence of corrosion, which consequently debilitates the shear strength of RC beams. This section reviews the influence of transversal reinforcement corrosion on the overall shear behavior of RC beams. It should be mentioned that the longitudinal steel corrosion can also weaken the shear capacity (through reducing of the dowel-action-resisting mechanism).

The key findings from the experimental programs along with the characteristics of 112 tests (112 number of specimens) investigating the shear capacity of RC members with corroded reinforcement are summarized in Table 3. Figure 7 presents the ratios of the shear capacity of the test with corroded shear reinforcement, V_{cor}, to the shear capacity of the intact test (control test), V_{con}, with respect to the mass loss, C_w, developed in shear (transversal) reinforcement. The average shear ratio V_{cor}/V_{con} is 0.80. Table 2 shows the statistical information of shear ratios; the minimum and maximum shear strengths of corroded beam are 0.42 and 1.21 times of their relevant control shear strengths. The following equation is proposed to determine the trend of the shear ratio

$$V_{cor}/V_{con} = -0.15\ln(C_w) + 0.6 \quad (14)$$

Fig. 6—Ratios of corroded moment (M_{cor}*) over control moment (*M_{con}*) capacities with respect to mass loss ratio (*C_w*).*

where C_c is the compressive force in concrete; c is neural axis depth; β_1 is the stress block factor; C_s is the compressive force in steel; d' is the depth to compressive bar; d is the depth to longitudinal reinforcement; c is the neural axis depth; T_c is the longitudinal force in concrete; h is the section height; ε_r is the flexural cracking strain corresponding to the modulus of rupture; ε_t is the longitudinal strain in reinforcing bar; and T_s is the longitudinal force in reinforcement.

Imam et al. (2015) applied the Artificial Neural Network (ANN) theory to predict the residual flexural capacity of RC beams. A method was proposed to predict moment capacity of beams using the compatibility concept as follows (Zhang et al. 2016)

$$M_u = F_c(h_0 - y() + F_s' h_0 - a_s') \quad (11)$$

where M_u is the flexural moment strength; F_c is the concrete compressive force; h_0 is the distance from top to steel centroid; $F_{s'}$ is the force of hanger bar; and $a_{s'}$ is the distance from the top to the centroid of hanger bar.

The moment-curvature and moment axial diagram of the section under corrosion was reported by Imperatore et al. (2016). Campione et al. (2017) explained that the moment capacity of a corroded member is the lower of the following statements

$m_{uy} = \alpha\gamma\omega_s$

d □□ □$1 - \delta - 2$

D_d

$- 0\,4.\; d\, x_{cu}$ □□ □(12)

$m_{uc}\; d\; d = \psi\, 0.125$ □□ □$1 - \delta - 2$

D_{d^2} □□ □(13)

where α is the stress block coefficient; γ is the dimension- less post-peak bond strength; ω_s is the mechanical ratio of steel bars; δ is the concrete cover thickness; d is the distance from the extreme compressive fiber to the centroid of the tension reinforcement; D is the bar diameter; x_{cu} is the position of neutral axis; and ψ is the ratio between the mean

Table 2—Statistical parameters of corroded-to- control ratios for moment and shear capacities

Statistical parameters	Moment ratio (M_{cor}/M_{con})	Shear ratio (V_{cor}/V_{con})
No. of tests	133	112
Average	0.87	0.80
Minimum	0.20	0.42
Maximum	1.39	1.21
Standard deviation	0.19	0.18
CoV	0.22	0.23

Table 3—Summary of experimental programs to evaluate shear capacity of corroded RC beams

f_c', MPa

No. of corroded test, No. of control test

Corroding $\rho_v f_y$,
method,
Loading MPa

μA/cm^2 steps

Test type Significant findings Reference

40.7 1.2 20,10 Acc*

(100) FC† FPB‡ Corresponding nominal shear force values may be determined using:

Reduced effective depth (d) and reduced reinforcement cross- sectional area (A_{vf}).

Rodriguez et al. (1997)

32.4 1.0 9,5 Acc (600) FC FPB Reduced areas on stirrups (pitting) lead to localized yielding and

reduced ductility.

Higgins and Farrow (2006)

26.2 0.8 8,2 Acc FC FPB Shear failure mode may change due to corrosion compared to

intact members. Wang et al. (2011)

21.0 0.5 8,8 Acc (100) FC FPB

Beam ductility was affected by corrosion. Reduced cross-sectional area of stirrups is reliable predictor of shear strength.

Juarez et al. (2011)

44.8 1.2 2,1 Env§ Sus|| TBP# Proposed strut-and-tie model was in close agreement with

experimental results of corroded beams. Khan et al. (2014)

44.1 1.2 12,4 Acc (200) FC FPB

In low stage of corrosion (5%), shear capacity was dropped approx- imately 5 to 25%. In high stage of corrosion (20%), shear capacity was dropped approximately 50 to 75%. In self-consolidating concrete (SCC) members, shear cracks observed in beams occurred in near-shear-span regions.

Lachemi et al. (2014)

34.5 0.5 8,2 Acc

(1000) FC TPB

Using minimum residual cross-sectional of most severely corroded section, shear strength could be evaluated accurately in accordance with “modified truss analogy” theory.

Xue et al. (2014)

45.9 1.2 8,2 Acc (200) FC FPB

Corrosion was less influential on load-carrying capacity of engineered cementitious composite (ECC) beams compared to normal concrete beams.

Sahmaran et al. (2015)

37.7 0.7 6,3 Acc (400) FC FPB

Stirrup with mass loss of 9% did not cause shear strength reduction. Measured crack width of concrete cover can be used as indicator of corrosion damage of stirrups.

El-Sayed et al. (2016)

33.1 1.6 13,2 Acc (400) FC FPB

Key parameters for corrosion damage include corrosion activity index, area of shear reinforcement, spacing of stirrups, cross-sectional details, and material strengths.

Imam and Azad (2016)

32.4 1.0 18,3 Acc (800) FC FPB

The corrosion and strength of concrete only affect shear strength, nor the failure mode. Ductility was reduced as a result of corrosion.

Xu et al. (2017)

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[*] Acc is accelerated corrosion applied. [†] FC is first corrosion induced and then tested. [‡] FP is four-point bending test. [§] Env is environmentally induced corrosion. [||] Sus is sustained loading while corrosion is induced. [#] TB is three-point bending test.

According to the data distribution, this study proposes a lower-bound equation to safely predict the shear strength of a corroded test based on the control shear strength and the ratio of mass loss $V_{cor}/V_{con} = -0.15\ln(C_w) + 0.35$ (15)

Equation (14) represents the average trend of corrosion affecting the shear capacity of RC beams, while Eq. (15) is a more conservative representation of the trend (to conservatively estimate the corroded shear strength with respect to the control shear strength).

Analytical studies on shear behavior

On the other hand, there have been research programs in the literature focused on numerical analyses to estimate the shear behavior of RC beams exposed to corrosion. Using a multi-mechanical approach with multi-directional fixed crack modeling, two-dimensional (2-D) post-cracking states of stresses and strains and shear cracks of concrete were simulated (Toongoenthong and Maekawa 2005). Xue et al. (2014) conducted a 2-D nonlinear analysis to investigate the shear behavior of RC members in the presence of corrosion. The results showed that due to poor anchorage, the stirrups slipped out of the concrete before their yield strength was fully attained. Thus, the truss mechanism was not formed, resulting in a significant decrease in shear strength.

Fig. 7—Ratios of corroded shear (V_{cor}) over control shear (V_{con}) capacities with respect to mass loss ratio (C_w).

The modified axial-shear-flexure interaction (MASFI) approach and its extension for corrosion (MASFI-C) were proposed by Ou and Nguyen (2016) to predict the behavior of corroded RC beams. Using the averages of residual cross-sectional area and strength properties of corroded reinforcement, the proposed MASFI-C was able to show the initial stiffness and strength behavior of RC beams before fracture of corroded reinforcement.

To acquire a shear model in the presence of corrosion in RC members, Higgins et al. (2012) modified shear models provided in the ACI approach (ACI 318-02; AASHTO 1996), Strut-and-Tie Method (STM) (ACI 318-02), Modified Compression Field Theory (MCFT) (AASHTO 2002), and Response-2000™ (Bentz 2000). Two types of corrosion effects were considered, including average mass loss and minimum cross-sectional area of stirrups left after corrosion. The proposed model, modifying the ACI approach, is as follows $V\ V\ V f\ b\ d^{A f d}$

$s^{n\ cor\ c\ cor\ s\ cor\ c\ weff}$

□ 0 0575 □ □□□□

□1 1 0 001 □ □$^{v\ eff}$= ^{s} – – ^{s} – □ □□□

□–

α

$7.53 + d^{9} \cdot d^{32} c$

^{2}□ □□□□ □(20)

$b_{eff} = b - 2(c + d_b) + \frac{s}{5.5}$ if $s \leq 5.5c$ (21)

$b_{eff} = b - \frac{s}{5 \cdot 5}(c + d_b)_2$

if $s > 5 \cdot 5c$ (22)

where A_s is the sound steel cross section (mm^2); w is the corrosion crack width (mm); α is the factor accounts for pit concertation (2 for homogenous corrosion; and between 4 and 8 for localized corrosion); d_b is the corroding bar diam- eter (mm); c is the concrete cover (mm); b is the original undamaged beam width; s is the stirrup spacing; and d is the depth of the tension steel. The mean of strength ratio using this model and six experimental specimens was 1.17.

Moreover, a simple sectional model for flexure and moment-to-shear interaction was proposed to predict shear capacity of corroded RC beams (Campione et al. 2017). El-Sayed (2017) proposed a strut-and-tie model for estimating the shear capacity of corroded RC deep beams, $a/d > 2.5$. Based on the MCFT, Zhang et al. (2017) also proposed a model to determine the shear behavior of RC beams with corroded stirrups.

In addition, an FEA was developed to predict the nonlinear behavior of RC members in shear through selecting adequate plane-stress finite elements for concrete and contact elements for bond-slip of the reinforcement (Coronelli and Mulas 2006; Kim 2008; Potisuk et al. 2011). Another FEA model, called 'EF2002', was a development of a previously created FEA model (Coronelli and Mulas 2001; Coronelli and Gambarova 2004). The mean value of nominal shear strength, using EF2002, was 1.01 times the experimental shear strength. The study showed that the uniform section loss up to 50% of the original area had a relatively small impact on strength.

The most common terms used in the literature to predict the reduced shear strength of RC beams in the presence of corrosion are as follows: reduced cross-sectional area of transversal reinforcement (A_v), yield strength of transversal reinforcement (f_y), corrosion rate (μA/cm^2), corrosion crack width (v), concrete cover (c), corrosion degree (%), effective depth of beam (d), shear span-to-effective depth ratio (a/d), and bond and anchorage capacities.

SUMMARY AND CONCLUSIONS The 2017 ASCE report card reported that the grade for the U.S. infrastructure overall at a "D+" and at a "C+" for the "Bridges" category (40% of U.S. bridges are more than 50 years old). Steel reinforcement corrosion in reinforced concrete (RC) members is mostly blamed for this deteri- orating trend of bridges. Many of these bridges cannot be rehabilitated and are still in use. Thus, there is an immediate □A , A .

□□□□ □ ^{w} A .

b

b

$= \quad + \quad = 2 \; ' +$

$v\_ \quad \_ \quad \_ \qquad yt$

(16)

where V_{n_cor} is the nominal shear resistance after corrosion (lb); V_{c_cor} is the shear resistance of concrete after corrosion (lb); V_{s_cor} is the shear resistance of transversal reinforcement after corrosion (lb); $f_{c'}$ is the compressive strength of concrete (psi); d is the effective depth (in.); f_{yt} is the yield strength of the transverse reinforcement (in.^{2}); s is the spacing of the trans- verse after corrosion, reinforcement and b(in.); $_{weff}$ is the A_v is the average area of stirrups effective concrete beam width available to resist shear that is determined from the following

$$b_{weff} = b_w - 2(c_v + \varnothing_v) + 5^{s}\ {}_{.5} \text{ if } s \leq 5.5(c_v + \varnothing_v) \quad (17)$$

$$b_{weff} = b_w - {}^{5}{}_{s}{}^{.5}(c_v + 0_v)^2 \text{ if } s > 5.5(c_v + 0_v) \quad (18)$$

where b_w is the original undamaged beam width (in.); c_v is the concrete cover (in.); and $Ø_v$ is the stirrup diameter. In the case of using minimum cross-sectional area left after corrosion, A_v is replaced by a minimum measured cross-sec- tional area of stirrups. The mean values of the strength ratio, the experimental to nominal shear strength, for the ACI approach, STM, MCFT, and Response 2000™ were 1.13, 1.09, 1.38, and 1.60, respectively. Furthermore, El-Sayed et al. (2016) proposed a model to determine the shear capacity of RC beams as follows

$$V^{n\,cor} V^{c\,cor} V^{s\,cor} fb^{c\,eff}$$

$$d^{A\,f\,d}\, s\ {}_{-} = {}_{-} + {}_{-}$$

$$= 0.17\lambda\,' + {}^{v,\,eff\,yv}$$

(19)

The effective area of stirrups, $A_{v,eff}$, and the effective concrete beam width, b_{eff}, resisting shear are calculated through the following equations

need to determine the residual structural strength of these RC members. This study presented a chronological litera- ture review on investigations of the mechanical behavior of concrete members, including shear and flexure, and high- lighted the significant findings of these research programs. The following key conclusions are drawn from this literature review:

1. In the literature, three methods have been used to corrode RC members in the experimental research programs, including accelerated, environmentally induced, and natural. There have been also two different loading sequences in the literature, including corroding the members before testing, and simultaneous corrosion and testing.

2. The flexural strength of 133 tests was used to propose a model estimating the reduced flexural capacity of corro- sion-damaged RC beams with respect to the mass loss ratio. The average moment ratio M_{cor}/M_{con} was 0.87 with the minimum of 0.20 and maximum of 1.39 (Table 2).

3. The shear strength of 112 tests with corrosion was used to create an imperial model for estimating reduced shear strength of RC beams with respect to the mass loss ratio of transversal reinforcement. The average shear ratio V_{cor}/V_{con} was 0.80 with a coefficient of variation of 0.23 (Table 2).

4. The most common parameters used in the literature to create analytical models estimating the shear and flexural strength of corrosion-damaged RC members include the wing: reduced cross-sectional area of reinforcement, mass ratio, corroding rate, yield strength of reinforce- ment, and r span-to-effective depth ratio.

5. More attention should be paid to increasing the ber of research programs investigating the mechanical vior of corrosion-damaged RC columns (due to their critical in structural systems to prevent global catastrophic collapses) to the corrosion influences in the mechanical behavior of ast members.

6. Most research programs conducted on mechanical vior of RC beams, regardless of the quality of these studies, been conducted outside the United States. This could propriately reflect the harsh environment specific to the ons in United States or the local construction prac- tices and iling.

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REFERENCES

AASHTO, 1996, "Standard Specifications for Highway Bridges," 16th edition, American Association of State Highway and Transportation, Washington, DC.

AASHTO, 2002, "Standard Specifications for Highway Bridges," 17th edition, American Association of State Highway and Transportation, Washington, DC.

ACI Committee 318, 2002, "Building Code Requirements for Structural Concrete (ACI 318-02) and Commentary (ACI 318R-02)," American Concrete Institute, Farmington Hills, MI, 443 pp.

ACI Committee 318, 2014, "Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)," American Concrete Institute, Farmington Hills, MI, 520 pp.

Aïtcin, P.-C., 2000, "Cements of Yesterday and Today: Concrete of Tomorrow," *Cement and Concrete Research*, V. 30, No. 9, pp. 1349-1359. doi: 10.1016/S0008-8846(00)00365-3

Al-Sulaimani, G. J.; Kaleemullah, M.; and Basunbul, I. A., Rasheeduzzafar, 1990, "Influence of Corrosion and Cracking on Bond Behavior and Strength of Reinforced Concrete Members," *ACI Structural Journal*, V. 87, No. 2, Mar.-Apr., pp. 220-231.

Ali, M. S.; Ji, C.; and Mirza, M. S., 2015, "Durable Design of Reinforced Concrete Elements against Corrosion," *Construction and Building Mate- rials*, V. 93, pp. 317-325. doi: 10.1016/j.conbuildmat.2015.05.011

Almusallam, A. A.; Al-Gahtani, A. S.; Aziz, A. R.; Dakhil, F. H.; and Rash- eeduzzafar, 1996, "Effect of Reinforcement Corrosion on Flexural Behavior of Concrete Slabs," *Journal of Materials in Civil Engineering*, ASCE, V. 8, No. 3, pp. 123-127. doi: 10.1061/(ASCE)0899-1561(1996)8:3(123)

Alonso, C.; Andrade, C.; Rodriguez, J.; and Diez, J. M., 1998, "Factors Controlling Cracking of Concrete Affected by Reinforcement Corro- sion," *Materials and Structures*, V. 31, No. 7, pp. 435-441. doi: 10.1007/ BF02480466

ASCE's 2017 Infrastructure Report Card | GPA: D+, 2017, http://www.infrastructurereportcard.org. (last accessed Sept. 15, 2017)

Azad, A. K.; Ahmad, S.; and Azher, S. A., 2007, "Residual Strength of Corrosion-Damaged Reinforced Concrete Beams," *ACI Materials Journal*, V. 104, No. 1, Jan.-Feb., pp. 40-47.

Azad, K.; Ahmad, S.; and Al-Gohi, B. H. A., 2010, "Flexural Strength Corroded Reinforced Concrete Beams," *Magazine of Concrete Research*, V. 62, o. 6, pp. 405-414. doi: 10.1680/macr.2010.62.6.405

Bentz, E. C., 2000, "Sectional Analysis of Reinforced Concrete embers," University of Toronto, Toronto, ON, Canada.

Cairns, J.; Du, Y.; and Law, D., 2008, "Structural Performance of orrosion-Damaged Concrete Beams," *Magazine of Concrete Research*, V. 60, o. 5, pp. 359-370. doi: 10.1680/macr.2007.00102

Cairns, J., and Zhao, M. A., 1993, "Behavior of Concrete Beams with posed Reinforcement," *Proceedings of the Institution of Civil Engi- neers. uctures and Buildings*, V. 99, No. 2, pp. 141-154. doi: 10.1680/ bu.1993.23373

Campione, G.; Cannella, F.; and Cavaleri, L., 2017, "Shear and Flexural ength Prediction of Corroded RC Beams," *Construction and Building aterials*, V. 149, pp. 395-405. doi: 10.1016/j.conbuildmat.2017.05.125

Capozucca, R., and Cerri, M. N., 2003, "Influence of Reinforcement rrosion—in the Compressive Zone—on the Behaviour of RC Beams," *gineering Structures*, V. 25, No. 13, pp. 1575-1583. doi: 10.1016/ 41-0296(03)00119-6

Castel, A.; François, R.; and Arliguie, G., 2000, "Mechanical Behaviour Corroded Reinforced Concrete Beams—Part 1: Experimental Study of Corroded ams," *Materials and Structures*, V. 33, No. 9, pp. 539-544. doi: 1007/BF02480533

Chen, Y.; Gao, J.; Tang, L.; and Shen, D., 2017, "Performance of ncrete Subjected to Severe Multiple Actions of Composite Salts Solu- tion er Wet-Dry Cycles and Flexural Loading in Lab,," *Journal of Wuhan iversity of Technology: Materials Science Edition*, V. 32, No. 4, pp. 830-837. i: 10.1007/s11595-017-1676-9

Coronelli, D., and Gambarova, P., 2004, "Structural Assessment of rroded Reinforced Concrete Beams: Modeling Guidelines," *Journal of uctural Engineering*, ASCE, V. 130, No. 8, pp. 1214-1224. doi: 10.1061/ SCE)0733-9445(2004)130:8(1214)

Coronelli, D., and Mulas, M. G., 2001, "Local-Global Approach in the Seismic Analysis of R/C Frames Including Bond Slip Effects," *Engineering Structures*, V. 23, No. 8, pp. 911-925. doi: 10.1016/S0141-0296(00)00116-4 Coronelli, D., and Mulas, M. G., 2006, "Modeling of Shear Behavior in Reinforced Concrete Beams," *ACI Structural Journal*, V. 103, No. 3, May-June, pp. 372-382.

Dekoster, M.; Buyle-Bodin, F.; Maurel, O.; and Delmas, Y., 2003, odelling of the Flexural Behaviour of RC Beams Subjected to Localized and niform Corrosion," *Engineering Structures*, V. 25, No. 10, pp. 1333- 1341. doi: 1016/S0141-0296(03)00108-1

Dong, W.; Ye, J.; Murakami, Y.; Oshita, H.; Suzuki, S.; and Tsutsumi, T., 2016, "Residual Load Capacity of Corroded Reinforced Concrete Beam undergoing Bond Failure," *Engineering Structures*, V. 127, pp. 159-171. doi: 10.1016/j.engstruct.2016.08.044

El Maaddawy, T.; Soudki, K.; and Topper, T., 2005, "Long-Term Perfor- mance of Corrosion-Damaged Reinforced Concrete Beams," *ACI Structural Journal*, V. 102, No. 5, Sept.-Oct., pp. 649-656.

El-Sayed, A. K., 2017, "Shear Capacity Assessment of Reinforced Concrete Beams with Corroded Stirrups," *Construction and Building Mate- rials*, V. 134, pp. 176-184. doi: 10.1016/j.conbuildmat.2016.12.118

El-Sayed, A. K.; Hussain, R. R.; and Shuraim, A. B., 2016, "Influence of Stirrup Corrosion on Shear Strength of Reinforced Concrete Slender Beams," *ACI Structural Journal*, V. 113, No. 6, Nov.-Dec., pp. 1223-1232. doi: 14359/51689147

Eyre, J. R., and Nokhasteh, Z., 1992, "Strength Assessment of Corro- n-Damaged Reinforced Concrete Slabs and Beams," *Proceedings of the stitution of Civil Engineers. Structures and Buildings*, V. 94, No. 2, pp. 197-203. i: 10.1680/istbu.1992.18788

Federal Highway Administration (FHWA), 2011, "Bridge Preservation ide," *Report No. FHWA-HIF-11042*, U.S. Department of Transportation, ashington, DC.

Feng, Q.; Visintin, P.; and Oehlers, D. J., 2018, "Effect of Steel Bar rrosion on Flexural Behaviour through Bond," *Proceedings of the Insti- tution Civil Engineers. Structures and Buildings*, V. 171, No. 5, May, pp. 380-394. doi: 1680/jstbu.16.00168

Gewertz, M. W., 1958, "Causes and Repair of Deterioration to a California Bridge Due to Corrosion of Reinforcing Steel in a Marine Environment Part I: Method of Repair," *Highway Research Board Bulletin 182*.

Halstead, L. A., 1955, "The Deterioration of Reinforced Concrete Structures under Coastal Conditions," *Civil Engineering (New York, N.Y.)*, V. 5, No. 10, pp. 353-372.

Han, S.-J.; Lee, D. H.; Kim, K. S.; Seo, S.-Y.; Moon, J.; and Monteiro, P. J., 2014, "Degradation of Flexural Strength in Reinforced Concrete Members caused by Steel Corrosion," *Construction and Building Materials*, V. 54, pp. 572-583. doi: 10.1016/j.conbuildmat.2013.12.101

Higgins, C., and Farrow, W. C. III, 2006, "Tests of Reinforced Concrete Beams with Corrosion-Damaged Stirrups," *ACI Structural Journal*, V. 103, No. 1, Jan.-Feb., pp. 133-141.

Higgins, C.; Farrow, W. C. III; and Turan, O. T., 2012, "Analysis of Reinforced Concrete Beams with Corrosion Damaged Stirrups for Shear Capacity," *Structure and Infrastructure Engineering*, V. 8, No. 11, pp. 1080-1092.

Imam, A.; Anifowose, F.; and Azad, A. K., 2015, "Residual Strength of Corroded Reinforced Concrete Beams Using an Adaptive Model Based on ANN," *International Journal of Concrete Structures and Materials*, V. 9, No. 2, pp. 159-172. doi: 10.1007/s40069-015-0097-4

Imam, A., and Azad, A. K., 2016, "Prediction of Residual Shear Strength of Corroded Reinforced Concrete Beams," *International Journal of Advanced Structural Engineering*, V. 8, No. 3, pp. 307-318. doi: 10.1007/s40091-016-0133-x

Imperatore, S.; Leonardi, A.; and Rinaldi, Z., 2016, "Strength Decay of RC Sections for Chloride Attack," *International Journal of Structural Integrity*, V. 7, No. 2, pp. 194-212. doi: 10.1108/IJSI-09-2014-0043

Jnaid, F., and Aboutaha, R. S., 2014, "Residual Flexural Strength of Reinforced Concrete Beams with Unbonded Reinforcement," *ACI Structural Journal*, V. 111, No. 6, Nov.-Dec., pp. 1419-1430. doi: 10.14359/51686975 Jnaid, F., and Aboutaha, R. S., 2016, "Residual Flexural Strength of Corroded Reinforced Concrete Beams," *Engineering Structures*, V. 119, pp. 198-216. doi: 10.1016/j.engstruct.2016.04.018

Johnson, P. M.; Couture, A.; and Nicolet, R., 2007, "Report of the Commission of Inquiry into the Collapse of a Portion of the de la Concorde Overpass," Gouvernement Du Québec, 222 pp.

Juarez, C. A.; Guevara, B.; Fajardo, G.; and Castro-Borges, P., 2011, "Ultimate and Nominal Shear Strength in Reinforced Concrete Beams Deteriorated by Corrosion," *Engineering Structures*, V. 33, No. 12, pp. 3189-3196. doi: 10.1016/j.engstruct.2011.08.014

Kallias, A. N., and Rafiq, M. I., 2010, "Finite Element Investigation of the Structural Response of Corroded RC Beams," *Engineering Structures*, V. 32, No. 9, pp. 2984-2994. doi: 10.1016/j.engstruct.2010.05.017

Kearsley, E. P., and Joyce, A., 2014, "Effect of Corrosion Products on Bond Strength and Flexural Behaviour of Reinforced Concrete Slabs," *Journal of the South African Institution of Civil Engineering*, V. 56, No. 2, pp. 21-29.

Khan, I.; François, R.; and Castel, A., 2014, "Experimental and Analytical Study of Corroded Shear-Critical Reinforced Concrete Beams," *Materials and Structures*, V. 47, No. 9, pp. 1467-1481. doi: 10.1617/ s11527-013-0129-y

Kim, S.-H., 2008, "NFEA Modeling of RC Beams Having Exposed Longitudinal Reinforcement: Effects of Debonding on Shear Behavior," University of Illinois at Urbana-Champaign, Champaign, IL.

Lachemi, M.; Al-Bayati, N.; Sahmaran, M.; and Anil, O., 2014, "The Effect of Corrosion on Shear Behavior of Reinforced Self-Consolidating Concrete Beams," *Engineering Structures*, V. 79, pp. 1-12. doi: 10.1016/j.engstruct.2014.07.044

Lewis, D. A., and Copenhagen, W. J., 1959, "Corrosion of Reinforcing Steel In Concrete in Marine Atmospheres," *Corrosion*, V. 15, No. 7, pp. 60-66. doi: 10.5006/0010-9312-15.7.60

Mancini, G., and Tondolo, F., 2014, "Effect of Bond Degradation due to Corrosion—A Literature Survey," *Structural Concrete*, V. 15, No. 3, pp. 408-418. doi: 10.1002/suco.201300009

Mangat, P. S., and Elgarf, M. S., 1999a, "Flexural Strength of Concrete Beams with Corroding Reinforcement," *ACI Structural Journal*, V. 96, No. 1, Jan.-Feb., pp. 149-158.

Mangat, P. S., and Elgarf, M. S., 1999b, "Strength and Serviceability of Repaired Reinforced Concrete Beams undergoing Reinforcement Corrosion," *Magazine of Concrete Research*, V. 51, No. 2, pp. 97-112. doi: 10.1680/macr.1999.51.2.97

McLeish, A., 1987, "Structural Assessment: Manual for Life Cycle Aspects of Concrete in Buildings and Structures," V. 4, Taywood Engineering Ltd., pp. 1-4.

Michel, A.; Pease, B. J.; Geiker, M. R.; Stang, H.; and Olesen, J. F., 2011, "Monitoring Reinforcement Corrosion and Corrosion-Induced Cracking Using Non-Destructive X-Ray Attenuation Measurements," *Cement and Concrete Research*, V. 41, No. 11, pp. 1085-1094. doi: 10.1016/j. cemconres.2011.06.006

Ou, Y.-C., and Nguyen, N. D., 2016, "Modified Axial-Shear-Flexure Interaction Approaches for Uncorroded and Corroded Reinforced Concrete Beams," *Engineering Structures*, V. 128, pp. 44-54. doi: 10.1016/j. engstruct.2016.09.031

Oyado, M.; Kanakubo, T.; Sato, T.; and Yamamoto, Y., 2011, "Bending Performance of Reinforced Concrete Member Deteriorated by Corrosion," *Structure and Infrastructure Engineering*, V. 7, No. 1-2, pp. 121-130. doi: 10.1080/15732471003588510

Palsson, R., and Mirza, M. S., 2002, "Mechanical Response of Corroded Steel Reinforcement of Abandoned Concrete Bridge," *ACI Structural Journal*, V. 99, No. 2, Mar.-Apr., pp. 157-162.

Potisuk, T.; Higgins, C. C.; Miller, T. H.; and Yim, S. C., 2011, "Finite Element Analysis of Reinforced Concrete Beams with Corrosion Subjected to Shear," *Advances in Civil Engineering*, V. 2011, pp. 1-14. doi: 10.1155/2011/706803

Rodriguez, J.; Ortega, L. M.; and Casal, J., 1994, "Corrosion of Reinforcing Bars and Service Life of Reinforced Concrete Structures: Corrosion and Bond Deterioration," *International Conference on Concrete across Borders*, Odense, Denmark, pp. 315-326.

Rodriguez, J.; Ortega, L. M.; and Casal, J., 1997, "Load Carrying Capacity of Concrete Structures with Corroded Reinforcement," *Construction and Building Materials*, V. 11, No. 4, pp. 239-248. doi: 10.1016/ S0950-0618(97)00043-3

Sahmaran, M.; Anil, O.; Lachemi, M.; Yildirim, G.; Ashour, A. F.; and Acar, F., 2015, "Effect of Corrosion on Shear Behavior of Reinforced Engineered Cementitious Composite Beams," *ACI Structural Journal*, V. 112, No. 6, Nov.-Dec., pp. 771-782. doi: 10.14359/51687749

Schmitt, G., 2009, "Global Needs for Knowledge Dissemination, Research, and Development in Materials Deterioration and Corrosion Control," World Corrosion Organization, New York.

Shayanfar, M. A.; Ghalehnovi, M.; and Safiey, A., 2007, "Corrosion Effects on Tension Stiffening Behavior of Reinforced Concrete," *Computers and Concrete*, V. 4, No. 5, Oct., pp. 403-424. doi: 10.12989/ cac.2007.4.5.403

Shayanfar, M. A., and Safiey, A., 2008, "A New Approach for Nonlinear Finite Element Analysis of Reinforced Concrete Structures with Corroded Reinforcements," *Computers and Concrete*, V. 5, No. 2, pp. 155-174. doi: 10.12989/cac.2008.5.2.155

Stratfull, R. F., 1957, “The Corrosion of Steel in a Reinforced Concrete Bridge,” *Corrosion*, V. 13, No. 3, pp. 43-48. doi: 10.5006/0010-9312-13.3.43

Tahershamsi, M., 2016, “Structural Effects of Reinforcement Corrosion in Concrete Structures,” Chalmers University of Technology, Gothenburg, Sweden.

Tahershamsi, M.; Zandi, K.; Lundgren, K.; and Plos, M., 2014, “Anchorage of Naturally Corroded Bars in Reinforced Concrete Struc- tures,” *Magazine of Concrete Research*, V. 66, No. 14, pp. 729-744. doi: 10.1680/macr.13.00276

Tanaka, Y.; Kawano, H.; Watanabe, H.; and Kimura, T., 2001, “Chloride-Induced Deterioration and Its Influence on Load-Carrying Capacity of Post-Tensioned Concrete Bridges,” Third International Conference on Concrete under Severe Conditions—Environment and Loading, Citeseer, pp. 495-502.

Ting, S.-C., and Nowak, A. S., 1991, “Effect of Reinforcing Steel Area Loss on Flexural Behavior of Reinforced Concrete Beams,” *ACI Structural Journal*, V. 88, No. 3, May-June, pp. 309-314.

Toongoenthong, K., and Maekawa, K., 2005, “Multi-mechanical Approach to Structural Performance Assessment of Corroded RC Members in Shear,” *Journal of Advanced Concrete Technology*, V. 3, No. 1, pp. 107-122. doi: 10.3151/jact.3.107

Torres-Acosta, A. A.; Fabela-Gallegos, M. J.; Munoz-Noval, A.; Vázquez-Vega, D.; Hernandez-Jimenez, J. R.; and Martinez-Madrid, M., 2004, “Influence of Corrosion on the Structural Stiffness of Rein- forced Concrete Beams,” *Corrosion*, V. 60, No. 9, pp. 862-872. doi: 10.5006/1.3287868

Torres-Acosta, A. A.; Navarro-Gutierrez, S.; and Terán-Guillén, J., 2007, “Residual Flexure Capacity of Corroded Reinforced Concrete Beams,” *Engineering Structures*, V. 29, No. 6, pp. 1145-1152. doi: 10.1016/j.engstruct.2006.07.018

Tremper, B.; Beaton, J. L.; and Stratfull, R. F., 1958, “Causes and Repair of Deterioration to a California Bridge Due to Corrosion of Reinforcing Steel in a Marine Environment. Part II: Fundamental Factors Causing Corrosion,” *Highway Research Board Bulletin 182*.

Vidal, T.; Castel, A.; and François, R., 2007, “Corrosion Process and Structural Performance of a 17-Year-Old Reinforced Concrete Beam Stored in Chloride Environment,” *Cement and Concrete Research*, V. 37, No. 11, pp. 1551-1561. doi: 10.1016/j.cemconres.2007.08.004

Vu, H. H.; Vu, N. A.; and François, R., 2014, “Effect of Corrosion of Tensile Rebars and Stirrups on the Flexural Stiffness of Reinforced Concrete Members,” *European Journal of Environmental and Civil Engi- neering*, V. 18, No. 3, pp. 358-376. doi: 10.1080/19648189.2014.881759

Wakeman, C. M.; Dockweiler, E. V.; Stover, H. E.; and Whiteneck, L. L., 1958, “Use of Concrete in Marine Environments,” *ACI Journal Proceedings*, V. 54, pp. 841-856.

Wang, L.; Li, C.; and Yi, J., 2015a, “An Experiment Study on Behavior of Corrosion RC Beams with Different Concrete Strength,” *Journal of Coastal Research*, V. 73, pp. 259-264. doi: 10.2112/SI73-046.1

Wang, L.; Ma, Y.; Ding, W.; Zhang, J.; and Liu, Y., 2015b, “Comparative Study of Flexural Behavior of Corroded Beams with Different Types of Steel Bars,” *Journal of Performance of Constructed Facilities*, V. 29, No. 6, p. 04014163 doi: 10.1061/(ASCE)CF.1943-5509.0000661

Wang, X.-H.; Gao, X.-H.; Li, B.; and Deng, B.-R., 2011, “Effect of Bond and Corrosion within Partial Length on Shear Behaviour and Load Capacity of RC Beam,” *Construction and Building Materials*, V. 25, No. 4, pp. 1812- 1823. doi: 10.1016/j.conbuildmat.2010.11.081

Wood, J. G. M., 2008, “Implications of the Collapse of the de la Concorde Overpass,” *Structural Engineering*, V. 86, No. 1, pp. 16-18.

Xia, J.; Jin, W.-L.; and Li, L.-Y., 2012, “Effect of Chloride-Induced ein- forcing Steel Corrosion on the Flexural Strength of Reinforced Concrete eams,” *Magazine of Concrete Research*, V. 64, No. 6, pp. 471-485. doi: .1680/macr.10.00169

Xu, S.; Zhang, Z.; Li, R.; and Qiu, B., 2017, “Experimental Study on e Shear Behavior of RC Beams with Corroded Stirrups,” *Journal of Advanced oncrete Technology*, V. 15, No. 4, pp. 178-189. doi: 10.3151/jact.15.178

Xue, X.; Seki, H.; and Song, Y., 2014, “Shear Behavior of RC Beams ontaining Corroded Stirrups,” *Advances in Structural Engineering*, V. 17, No. 2, . 165-177. doi: 10.1260/1369-4332.17.2.165

Yu, L.; François, R.; Dang, V. H.; L’Hostis, V.; and Gagné, R., 2015, evelopment of Chloride-Induced Corrosion in Pre-cracked RC Beams under istained Loading: Effect of Load-Induced Cracks, Concrete Cover, and Exposure onditions,” *Cement and Concrete Research*, V. 67, pp. 246-258. doi: .1016/j.cemconres.2014.10.007

Yuan, Y.; Ji, Y.; and Shah, S. P., 2007, “Comparison of Two ccelerated Corrosion Techniques for Concrete Structures,” *ACI Structural urnal*, V. 104, No. 3, May-June, pp. 344-347.

Zhang, W.; Ye, Z.; and Gu, X., 2017, “Effects of Stirrup Corro- sion on ear Behaviour of Reinforced Concrete Beams,” *Structure and Infrastructure ngineering*, V. 13, No. 8, pp. 1081-1092. doi: 10.1080/15732479.2016.1243563

Zhang, X.; Wang, L.; Zhang, J.; and Liu, Y., 2016, “Bond Degrada- on-Induced Incompatible Strain between Steel Bars and Concrete in Corroded RC eams,” *Journal of Performance of Constructed Facilities*, V. 30, No. 6, p. 016058 doi: 10.1061/(ASCE)CF.1943-5509.0000921

Zhou, Y.; Gencturk, B.; Willam, K.; and Attar, A., 2015, “Carbon- ion-Induced and Chloride-Induced Corrosion in Reinforced Concrete Structures,” *urnal of Materials in Civil Engineering*, ASCE, V. 27, No. 9, p. 04014245 doi: .1061/(ASCE)MT.1943-5533.0001209

Zhu, W., and François, R., 2014, “Corrosion of the Reinforcement and Influence on the Residual Structural Performance of a 26-Year-Old Corroded Beam,” *Construction and Building Materials*, V. 51, pp. 461-472. doi: .1016/j.conbuildmat.2013.11.015

Zhu, W.; François, R.; Cleland, D.; and Coronelli, D., 2015, “Failure ode Transitions of Corroded Deep Beams Exposed to Marine Environ- ment for ng Period,” *Engineering Structures*, V. 96, pp. 66-77. doi: .1016/j.engstruct.2015.04.004

Zhu, W.; François, R.; Coronelli, D.; and Cleland, D., 2013, “Effect of orrosion of Reinforcement on the Mechanical Behaviour of Highly Corroded RC eams,” *Engineering Structures*, V. 56, pp. 544-554. doi: .1016/j.engstruct.2013.04.017

Zhu, W.; François, R.; Fang, Q.; and Zhang, D., 2016, “Influence of ng-Term Chloride Diffusion in Concrete and the Resulting Corrosion of einforcement on the Serviceability of RC Beams,” *Cement and Concrete omposites*, V. 71, pp. 144-152. doi: 10.1016/j.cemconcomp.2016.05.003