Dejian Shen

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Foreword

Reinforced concrete (RC) structures have been widely utilized in civil engineering and hydraulic engineering. However, the carbonation of the concrete cover or excessive chloride penetration of RC structures will lead to reinforcement corrosion. Reinforcement corrosion will deteriorate the safety and durability of RC structures and members such as beams, columns, beam–column joints, and shear walls. Therefore, reliable and effective methods should be proposed to retrofit these corroded RC structures and members. Recently, fiber-reinforced polymer (FRP) has been commonly utilized for strengthening or retrofitting RC members due to the advantages of lightweight, high tensile strength, and corrosion resistance.

In order to explore the influence of reinforcement corrosion on the performance of RC structures and propose practical retrofitting techniques, Prof. Dejian Shen and his team made several innovative and in-depth achievements by combining theoretical research with engineering practice to evaluate the performance and retrofit corroded RC structures with basalt FRP (BFRP) sheets. This monograph introduces the evaluation technique for the performance of corroded RC members, develops the effective anchorage techniques for retrofitting the corroded RC members with BFRP sheets, proposes the models for the load-bearing capacities of corroded RC members and corresponding members retrofitted with BFRP sheets, and explores the bond behavior between BFRP sheets or bars and concrete under static and dynamic loadings. The achievements have been successfully applied in some projects to increase the safety and durability of RC structures, and promote the development of the retrofitting technique of corroded RC structures.

This monograph is a systematic summary of the research of the author and his team on seismic assessment and retrofitting of corroded RC structures during the recent two decades. As a high-level professional monograph, it provides valuable knowledge, useful methods, and practical experience that can be utilized for the retrofitting of RC structures. The research achievements that make up this monograph are well presented and the evaluating and retrofitting techniques for different corroded RC members are clearly clarified. This monograph can not only be used as a reference for teachers and students in university, but also guide the majority of engineering and technical personnel to promote the development of the retrofitting technique of corroded RC structures with FRPs in practice.

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Preface

Reinforced concrete (RC) structure is the main structural form and has been widely used in the building engineering, marine engineering, transportation engineering, etc. RC structure permanently exposed to the atmosphere or other situations such as the deicing salt, acid environment, and environmental pollution, or chloride penetration in the marine environment, resulting in the reinforcement corrosion and concrete carbonation. The effective areas and nominal yielding strength of bars decreased since the reinforcing bars corroded; subsequently, the bond behavior between the reinforcing bars and concrete deteriorated. Then, the seismic performance of RC members such as beams, columns, beam-column joints, and shear walls decreased after the reinforcing bars corroded, affecting the durability and service performance of structures. Besides, several methods had been developed to repair or retrofit the corroded RC members, such as the increasing section area, concrete replacement, and bonded steel method. Nowadays, the fibers such as steel fiber or fiber-reinforced polymer (FRP) have been more available for retrofitting or strengthening the RC structures. Due to the benefits of lightweight, high tensile strength, and outstanding corrosion resistance, FRP has attracted the concentrations of scholars. Ordinary FRP composites such as AFRP, GFRP, CFRP, and HFRP have been commonly utilized to retrofit or strengthen the RC beams, columns, beam-column joints, and shear walls. However, the expenses of GFRP and CFRP are extremely high for the engineering. The poor chemical stability, heat resistance, and alkali resistance of GFRP can be found in literatures. Electric conduction of CFRP sheets can be found in literatures, resulting in potential dangers for the practical application in engineering. Furthermore, BFRP considered as a preferable high-performance fiber material has been applied for the sake of high resistance of acid, high tensile stress, low expense, and excellent ductility. Despite the fact that the elastic modulus and failure stress of BFRP are lower than those of CFRP, the tensile strength of BFRP is higher than those of AFRP or GFRP, and better performance found in acidic environments than GFRP. Besides, better bond behavior between BFRP sheet and concrete than that between CFRP sheet and concrete can also be found in literatures. In particular, the RC members strengthened with BFRP exhibit higher ductility than those strengthened with CFRP, which may attribute to the larger ultimate strain of BFRP.

Therefore, BFRP exhibited excellent advantages in the application of engineering. However, systematic investigations on the seismic performance of corroded RC structures retrofitted with BFRP sheets remain lacking. Therefore, this monograph focus on the investigations on the applications of BFRP sheets in retrofitting the corrosion-damaged RC structures.

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Dr. Ming Li prepared the draft for Chaps. 1, 5, and 6. Dr. Chuyuan Wen prepared the draft for Chaps. 1, 2, and 7. Dr. Jiaojiao Yuan prepared the draft for Chaps. 1, 2, and 4. Dr. Da Zong prepared the draft for Chaps. 1 and 3. Team members in the author's research group made a great contribution to the preparation of this monograph, including Mr. Zhihao Wang, Mr. Yifan Wei, Mr. Haokang Wang, Mr. Jingwang Yao, Mr. Hanbin Xu. Graduate students in the author's research group contributed a great deal to the research work and completion of this monograph, including Dr. Chengcai Li, Dr. Yang Jiao, Mr. Xingzuo Liu, Mr. Xuan Zeng, Mr. Huafeng Shi, Mr. Xiang Shi, Mr. Yong Ji, Mr. Shucheng Deng, Mr. Qun Yang, Mr. Zhenghua Cui, Mr. Ming Li, Mr. Yunshang Qi, Ms. Tian Tian, Mr. Wei Wang, Mr. Peng Du, Mr. Haifeng Su, Mr. Bin Wang, Mr. Jun Du, Mr. Binod Ojha, Ms. Fenfang Yin, Ms. Qianyan Jiang, Ms. Jiaojiao Yuan, Mr. Congbin Huang, Ms. Jie Yang, Ms. Ling Song, Mr. Sen Qiu, Mr. Jinkun Li, and Mr. Cong Li. Their hard-working, dedication, and intelligence have contributed considerably to the work presented in this monograph.

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Abbreviations

AFRP	Aramid fiber-reinforced polymer
BFRP	Basalt fiber-reinforced polymer
CFRP	Carbon fiber-reinforced polymer
FE	Finite element
FRP	Fiber-reinforced polymer
GFRP	Glass fiber-reinforced polymer
HFRP	Hybrid fiber-reinforced polymer
HPB	Hot-rolled plain steel bar
HRB	Hot-rolled ribbed steel bar
IAE	Integral absolute error
LVDT	Linear variable differential transducer
RC	Reinforced concrete

Chapter 1
Introduction

1.1 Corrosion and Retrofitting of Structures

1.1.1 Seismic Performance of Corrosion-Damaged Structures

RC structure is the main structural form and has been widely used in the building engineering, marine engineering, transportation engineering, etc. The durability and seismic performances of RC structure have always been a hot topic [1–5]. However, the reinforcement corrosion is one of the main reasons for the deterioration of the RC structure. According to relevant reports, nearly 50% of China's existing houses entered the aging stage, and nearly 250 billion square meters of buildings had to face durability issues [6]. According to the NIST report [7], the United States lost nearly $300 billion annually due to corrosion of reinforcing bars. In Japan, the annual cost of only maintaining housing structures has reached 40 billion yen, and about 21.4% of the damage to RC structures is caused by corrosion of reinforcing bars. In China, the direct economic loss caused by the corrosion is 500 billion yuan per year, and the loss of concrete structure damage caused by the reinforcement corrosion is 100 billion yuan per year [8]. Therefore, the reinforcement corrosion has aroused relevant attentions.

Reinforcement corrosion is mainly caused by the exposure to atmosphere or other situations such as the deicing salt, acid environment, and environmental pollution, or chloride penetration in the marine environment [9]. The effective areas and the nominal yielding strength of reinforcing bars decreased since the reinforcing bars corroded. Results reported in [10] indicate that the main reason for the degradation of bearing capacity of RC member is that the corrosion of reinforcing bars contributes to the biaxial tensile and compressive stresses in the concrete in the compression zone. Corrosion of reinforcing bars not only leads to loss of cross-sectional area, but also leads to degradation of mechanical properties of reinforcing bars. Results reported in [11] find that when the section loss rate of reinforcing bars is less than 5%, the mechanical properties of corroded reinforcing bars are the same as those

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of the base metal, indicating that small corrosion rates have no impact on structural performance. When the loss rate of reinforcing bars is between 5% and 10%, the yielding strength, tensile strength, and elongation decrease. When the slope loss rate of the reinforcing bars is between 10% and 60% and the reinforcing bar is severely pitted, the yielding point is no longer obvious, and the actual strength of reinforcing bars decreases significantly. The non-uniformity and dispersion, as well as the losing strength of reinforcing bars increase with the increasing of corrosion rates. Results reported in [12] indicate that the ductility of reinforcing bars decreases significantly with the increasing of the corrosion rate, and brittle failure of reinforcing bars occurs when the corrosion rate is greater than 12%. Results reported in [13] indicate the mechanical properties of 123 corroded reinforcing bars in atmospheric condition, indicating that the significant linear relationship between yielding load, ultimate load, and ultimate elongation of corroded reinforcing bars and corrosion rate can be found. Besides, a three-dimensional ellipsoidal model of corroded reinforcing bars and a method for measuring the corrosion rate of reinforcing bars are proposed.

Besides, corrosion of reinforcing bars not only reduced the mechanical properties and effective cross-sectional area of the reinforcing bars, but also changed the bond behavior between the reinforcing bars and concrete. Results reported in [14] conduct the experimental tests on the performance of corroded specimens by the pull-out tests, indicating that the bond strength between the reinforcing bars and concrete slightly increases when the corrosion rate of reinforcement is less than 1%. As the corrosion rate of reinforcing bars increases, the bond strength between reinforcing bars and concrete begins to decrease. Results reported in [15] find that the average bond stress decreases rapidly by 9% and 92% when the corrosion rates are 4% and 17.5%, respectively, indicating that transverse ribs of reinforcing bars are severely rusted, and the bond strength between reinforcing bars and concrete decreases when the reinforcing bars significantly corroded. Results reported in [16] indicate that the bond behavior between reinforcing bars and concrete significantly degrades after the reinforcing bars corroded, and the degradation is mainly related to the corrosion rate, the diameter, and the thickness of concrete protective layer.

Furthermore, since the reinforcing bars corroded, the load-bearing capacity and safeness of RC members would also decrease significantly. Results reported in [17] find that the ununiformity of corrosion and rust pits can be observed on the corroded RC beams. When there is a coupling effect of load and corrosion on the beam, the deflection of the beam will increase with the increase of corrosion rate, and with the increase of corrosion rate, the failure mode of RC beams will change to bending failure accompanied by bond splitting failure. For beams with cracks, the bearing capacity decreases significantly when the corrosion rate is low, indicating that the reduction in bearing capacity is related to the stress concentration caused by uneven corrosion of the reinforcement. Results reported in [18] find that the shear resistance of beams decrease after the stirrups corroded, contributing to the brittle failure of beams. The degradation of the bond behavior between corroded stirrups and concrete results in a significant nonlinear relationship between the bending moment and deflection in the beam span. Moreover, the section ductility and stiffness of severely corroded beams will decrease as the corrosion rate increases, and a method for predicting the bearing capacity of corroded beams is proposed. Results reported in [19] indicate that the energy dissipation and load-bearing capacities of corroded beam-column joints apparently decrease after reinforcing bars corroded, which results in the brittle failure mode.

Furthermore, the mechanical property of the reinforcing bars, bond behavior between reinforcing bars and concrete, as well as the performance of RC beams, columns, beam-column joints, and shear walls significantly decreased after the reinforcing bars corroded. Therefore, investigations on the seismic performance of corroded RC members retrofitted with certain methods are necessary.

1.1.2 Retrofitting of Structures

Buildings are one of the important disaster bearers of earthquake disasters. The increasing earthquake casualties and economic losses are mainly attributed by damage, failure, destruction, and collapse of the disaster bearers caused by strong earthquake action. Therefore, the seismic resistance of building structures is the key to ensure structural safety and use functions [20]. As an important component of the frame, RC beam-column joints are also weak links in the structure, and their seismic performance is the top priority in design. Due to the frequent occurrence of earthquake disasters, changes in temperature environment, construction factors, design changes, changes in use functions, and other reasons in recent years, the seismic performance of existing RC members cannot meet the seismic fortification standards, and it is necessary to repair and strengthen them [21].

Presently, the traditional retrofitting methods of concrete structures mainly include the followings [22]: increasing section method, replacing concrete method, external prestressing method, external bonding steel method, bonding steel plate method, bonding fiber-reinforced composite material method, and so on. Therefore, scholars have conducted extensive researches on repairing and retrofitting techniques.

Recently, FRP has been commonly utilized for strengthening or retrofitting the RC members owing to the advantages of light weight, high tensile strength, corrosion resistance, and easy installation [23–26]. Although conventional FRP composites, such as the CFRP [27–29], GFRP [30], AFRP [31], and HFRP [32], have been applied to strengthen the RC members, a few deficiencies cannot be avoided. As the most expensive composite among those mentioned above, the CFRP exhibited the highest strength and elastic modulus; however, the ultimate tensile strength could not be obtained attributed to the debonding instead of rupturing. The GFRP exhibited relatively weak performance in the properties of thermal stability, heat resistance, and alkali resistance [33, 34]. In addition, as a new type of inorganic eco-friendly high-performance fiber material, the BFRP with the advantages of high tensile stress, acid resistance, and excellent ductility is also commonly applied [35–37]. A higher ductility than that of CFRP makes the BFRP exhibit a larger ultimate strain, which is beneficial for RC members to maintain the ductility under the earthquake [38, 39]. Presently, investigations on the bond behavior of concrete members reinforced by BFRP bars under the static load [36, 37], dynamic load [24], cyclic load [40], the bond stress-slip relationship between BFRP sheets and concrete [41, 42], as well as the effective bond length of the BFRP-concrete interface [43] have been conducted. Besides, utilizing the BFRP to strengthen the RC beams and shear walls was preliminarily studied as well. Results reported in [44] indicate that the BFRP sheets can bear moment prior to the steel plate, which is also utilized to strengthen the pre-cracked RC beams, and completely exhibit the excellent tensile performance. Results reported in [33] indicate that the load-bearing capacity and ductility of RC shear walls are significantly improved after strengthening with BFRP strips. Furthermore, results reported in [34] also indicate that the failure mode of unreinforced masonry walls is altered from the shear failure to flexural failure, and the shear capacities are significantly improved with the application of BFRP. Although investigations on the seismic performance of RC members strengthened with BFRP have been studied, investigations on the comparisons of RC members strengthened with different methods are relatively limited. Therefore, further investigations on the RC members strengthened or retrofitted with BFRP for better understanding the efficiency of BFRP are needed.

1.2 State-of-the-Art of Retrofitting of Structures

1.2.1 Bond Stress-Slip Relationship Between FRP Sheets and Concrete

Factors such as environmental attack, fatigue damage, and lacking of appropriate maintenance have a negative influence on the service life of civil infrastructures [33]. The strengthening and rehabilitation of these structures proved to be costly. Accordingly, FRP sheets, which are less demolition of damaged RC with lower related costs, have been widely used to strengthen damaged RC [45, 46]. Determining the bond behavior between the FRP sheets and concrete is an important issue because the typical failure mode between the FRP sheets and concrete is debonding. When cracks are developed in concrete, FRP debonding is triggered by the stress concentration [47], which is considered an early failure mode of rehabilitated RC structures [48]. The bond behavior between FRP and concrete is mainly affected by the stiffness of FRP [49–52], the mechanical and physical properties of concrete [53–57], the thickness of the adhesive [35], and bond length [39]. In addition, numerous methods have been suggested to predict the effective bond length [58–61], the failure load [62–64], and the local shear stress-slip relationship between FRP sheets and concrete [65, 66].

Although BFRP sheets are available to be used in damaged RC, the bond behavior between BFRP sheets and concrete is still lacking. Three methods can be used for evaluating the bond behavior between FRP sheets and concrete: (1) FE analyses

[67]; (2) shear tests with strain gauges attached to the FRP sheet [68]; and (3) local bond-slip law [69, 70]. The second method was used in this book.

The force induced in the FRP sheets is transmitted to concrete mainly through bond stress in the adhesive. However, the transfer length of bond stress is limited, and the effective bond length is defined as the bond length beyond which no further increase of failure load can be achieved [59]. Then, extending the bond length to raise the failure load cannot be proved beneficial when it is beyond the effective bond length. Three methods can be used to assess the effective bond length: (1) the failure load [71, 72]; (2) the bond length obtained from the distance between 10% of the maximum bond stress [35, 57]; and (3) length over which strain decreases from the maximum value to 0 [39, 51]. In the first method, the range of the effective bonding length could be achieved. In the second or third method, the accurate value of the effective bonding length could be achieved.

RC structures in civil engineering are exposed to dynamic loadings. Moreover, concrete has a higher dynamic strength and fracture toughness than its corresponding static values [73, 74]. Numerous investigations on RC structures retrofitted with FRP under dynamic loadings have been conducted. Through experiments and models, the blast resistance of structures externally reinforced with FRP has also been studied [75, 76]. By regression analysis on bond data, it was discovered that the bond between FRP and concrete grows logarithmically with strain rate [77]. The effective length of the interface between FRP sheet and concrete will shorten as the strain rate increases and the interfacial fracture energy of FRP and concrete increases with strain rate as a logarithmic function. To date, the models for estimating the dynamic effective bond length of the interface between FRP and concrete under dynamic loadings at various strain rates are lacking.

1.2.2 Behavior of Beams Retrofitted with FRP

Cracking is normal in RC structures [78–81], and local cracks that result from overloading, the flaws of the construction technology, and other causes inevitably occur during the design life of RC structures. The load-bearing capacity of RC structures decreases after years of service because of the cracking of concrete and the reinforcement corrosion [82]. The occurrence of cracks in a structure affects its dynamic characteristics, such as natural frequency, stiffness, damping properties, and mode shape [83], and even adversely affects the durability and security of the structure [84]. The natural frequencies of cracked beams can provide insight into the extent of damage, and the research has been conducted to develop vibration-based inspection techniques for a wide range of applications [84]. Damage detection and structural performance monitoring, especially for the case of crack detection in RC structures, have been conducted on the basis of this effect [85]. Data on the performance of old RC beams with cracks is required to offer a reference for detection and repair [86].

The natural frequency of cracked beams has raised considerable research interest in recent years [87]. Natural frequency is a global property of structures, in which any change signifies a change in characteristics [78]. Monitoring the performance of RC beams on the basis of the vibration response is reliable and economical [88]. Many experimental modal tests have been conducted to detect damage. The frequency response obtained with an appropriate signal processing technique such as Hilbert-Huang transform is used to infer the performance of monitored structures [78]. The damage detection schemes used in [85] depended on the measured changes in the first three natural frequencies and the corresponding amplitudes of the measured acceleration frequency response functions. Various methods based on the measurement of natural frequencies have been proposed to detect the location and size of a crack in RC beams. The point of intersection of the three curves gives the crack location, and the crack size is then computed using the standard relation between stiffness and crack size [89]. A method is presented which uses the modal parameters of the lower modes for the non-destructive detection and sizing of cracks in beams [90, 91]. A simple and easy non-destructive evaluation procedure is presented for identifying a crack in a beam type structure using the lowest four natural frequencies test data [92]. The results of the forced responses of the free end point for a cracked cantilever beam are also shown to present the crack effects for crack extents and crack locations [93]. Several methods consider RC beams as Euler-Bernoulli beams [94–96], while the effects of shear deformation and rotational inertia are considered through Timoshenko beam theory in other methods [97–99]. Meanwhile, several techniques for the calculation of natural frequencies of RC beams with a number of open cracks have been proposed. The natural frequencies of a cracked beam are evaluated by representing cracks as massless springs and using a continuous mathematical model of the beam in transverse vibration [87]. The natural frequencies and mode shapes of a cracked beam are obtained using the FE method [100]. The FE and component mode synthesis methods are used together to analyze the free vibration [101]. The forced response is determined by employing modal series expansion technique [102]. Although the model for the frequency of RC beams with one or two flexural cracks has been proposed [88], the method for calculation of the frequency of RC beams with numerous cracks remains lacking.

Deflection is often utilized to evaluate beam performance, which is affected by stiffness. Stiffness reduction is an important indication of crack development. The full-scale loading test is effective in evaluating the performance of an old beam [86]. Destructive tests on 40-year-old girders are conducted to determine their ultimate load-bearing capacities and deflections [103, 104]. Full-scale tests on 30-year-old girders at varying shear span-to-depth ratios are conducted to evaluate their behavior, failure mode, and capacity [105]. Tests on the load-bearing capacity and deflection of a severely distressed and deteriorated 50-year-old RC box beam of bridge are conducted [106]. Full-scale tests on old RC box beams are rare because of the high cost of performing the tests and the limited availability of existing deteriorated beams for testing [86]. The test on the deflection of RC beams with damage has also been rarely investigated. Severe damages on the beam indicates high loss of stiffness [107], and stiffness change affects the deformability of RC beams [108]. The effective moment of inertia for the short-term deflection of cracked non-prestressed and prestressed concrete members is proposed [109], which is called Branson's method and is recommended by several standards [110, 111]. The deflection of cracked RC beams under long-term has also been investigated, and test results show that the overall stiffness of beams is substantially reduced after six months under sustained loading [112].

Stiffness is a significant parameter of the structural characteristics [113]. Dynamic tests have validated that the natural frequency is useful for detecting damage and stiffness change in RC beams [114]. However, the dynamic behavior of beams with initial flexural cracks strengthened with FRP sheets has not been investigated thoroughly [115]. Results reported in [116, 117] investigated the effectiveness of modal testing in assessing the variations of overall stiffness of RC beams extensively cracked and subsequently repaired with FRP sheets. Zanardo et al. conduct vibration tests and modal analysis on a bridge structure before and after retrofitting with FRP and determine that the upgrading works resulted in an increase of 26% to 32% in the experimental flexural stiffness, respectively [113].

Favorable failure mode is the flexural failure due to either concrete crushing or rupture of tensile reinforcement. Adequate precautions should be taken to postpone the other two failure modes: shear failure and FRP debonding [118]. The most available methods in calculating load-bearing capacity of strengthening RC beams have not considered the influence of end anchorage. Common strengthening method without end anchorage may lead to premature failure. Some studies are conducted to investigate the premature failure of FRP systems. Results in [60] show that interfacial stresses between concrete and reinforcing FPR may produce a sudden and premature failure and a simplified procedure for verifying the interfacial stress state. A cohesive zone model is adopted in a FE code for simulating the debonding failure in composite structures [119]. Results in [120] show that surface preparation prior to bonding of FRP sheets increases ultimate rupture strength and can postpone the premature failure. End anchorage is an important method that can reduce the probability of FRP debonding and has been recently suggested for prevention of the premature FRP debonding [121]. End anchorage improves the performance of the strengthened beams, particularly increasing the load-bearing capacity and cracking characteristics, and also changes the failure modes [122]. There are different methods for end anchorage, the most common being the use of FRP U-strips, FRP fan anchors, steel plates with bolts [123], anchors bolts or fasteners [124], and steel clamps [125]. In addition, there are no design codes or guides for the calculation for BFRP-strengthened beams anchored with new methods [126]. In most cases, orientation of U-strips transverse FRP composites perpendicular to the beam longitudinal axis can meet the general requirements for shear strengthening [127]. Results in [128] show that the RC beam shear-strengthened with FRP strips can significantly increase the shear capacity. Placement of U-strips nearby the end of beam also prevents the concrete cover delamination, which in turn postpones the FRP debonding. However, in previous studies, the debonding failure is still appeared to be almost inevitable in the presence of U-strips [129, 130]. Grooving is widely utilized in near-surface mounted method. The steel reinforcement is embedded in grooves cut onto the surface of the beam to be strengthened and filled with an appropriate binding agent such as epoxy paste or cement grout [131]. Results in [132] show that grooving as near-surface mounted method can increase the load-bearing capacities of RC beams. Results in [120] show that grooving as an alternative method of surface preparation is able to postponed FRP debonding in RC beams.

The behavior of RC beams strengthened with FRP strips is significantly influenced by cracks. For RC beams strengthened with FRP strips in tension face, intermediate crack-induced debonding may arise as a major flexural crack or flexural-shear crack [133]. Externally bonded CFRP strips can achieve adequate repair on corroded and cracked RC beams [134]. CFRP or GFRP sheets placed perpendicular to the shear crack significantly strengthen RC beams [135, 136]. Standards corresponding to externally bonded FRP systems to strengthen concrete structures have been published [137, 138]. Most investigations have been conducted to focus on undamaged or uncracked beams [139]. Seven RC beams were poured in advance in [140] to study the failure modes of RC beams strengthened in shear with CFRP strips. Six RC beams were cast in place in [141] to analyze the RC beams strengthened in flexure using CFRP laminates under sustaining load. The stress-strain relationship of FRP-strengthened beams without initial cracks is studied in [142], and the results show that the load history can be used to define a design criterion for predicting the safe load levels.

The flexural failure of structures is a favorable failure mode, which may be caused by the crush of concrete or the rupture of tensile bar [143]. FRP debonding and shear failure should be postponed through adequate precautions as other two failure modes [144]. The application of end anchorages improves the load-bearing capacity and cracking characteristics of strengthened beams, and the failure modes may be changed [120]. Various methods have been proposed to meet the requirement of the anchorage, among which the FRP U-strips are the most common ones [144]. However, the effect of anchorage is not considered in most existing calculating methods when evaluating the load-bearing capacity of FRP-strengthened beams [145]. This condition may lead to premature failure of the beams, which is a hot issue and has been investigated in recent years [60]. The results demonstrated in [128] show that the concrete cover delamination will be prevented when the FRP U-strips are placed nearby the ends of FRP-strengthened RC beams, and the FRP debonding will be postponed under this condition. However, several investigations show that the debonding failure still appears when the FRP U-strips are utilized in the strengthened RC beams [146]. Steel plates have been utilized widely to strengthen the RC beams with FRP composites in recent years and proved to be effective and valuable [147]. The steel plate anchorage refers to the application of steel plates with anchor bolts to fix the FRP composites on the concrete structures and members [42]. The steel plates can be placed along the entire length of the FRP strips, which is called full-length mechanical anchoring or only at both ends of the FRP sheet, which is called end mechanical anchoring. The results demonstrated in [148] show that the application of steel plates as well as externally bonded FRP can prevent the premature FRP debonding.

1.2.3 Seismic Performance of Columns Retrofitted with FRP

Many coastal zones are vulnerable to encountering earthquakes. RC columns in these areas are vulnerable to the combined effects of tremors and corrosion. Corroded RC columns are anticipated to function seismically much worse than their intended performance [149, 150]. Characterizing the seismic performance of corroded RC columns has been the subject of studies over the past 20 years [151–154]. Higher corrosion levels and axial loads produce less stable hysteretic loops with more extreme stiffness and strength degradations as well as worse ductility. Six rectangular cast-in-place RC columns of varying corrosion levels are studied in [155], which identifies two main effects of structural performance degradation: concrete cover crack and diminished mechanical properties of corroded reinforcing bars. Four columns with varying degrees of corrosion are subjected to cyclic pseudo-static tests in [156], which concludes that corrosion has a substantial impact on load-bearing capacity.

In order to solve the corrosion of reinforcing bars, the traditional method is to repour the concrete cover. Damaged concrete covers and rust from corroded reinforcing bars are normally removed from the degraded columns to restore them. Next, cleaning reinforcing bar is covered with a corrosion-resistant coating layer. And finally, a fresh layer of concrete is added to the columns. This conventional procedure is time-consuming, needs highly trained labor, and is particularly less effective than employing FRP strengthening techniques [157–162]. FRP has great corrosion resistance, high tensile strength, and lightweight and is easy to fabricate. Much research on the structural behavior (capacity, stiffness, and deformation) of FRP retrofitting RC columns with virgin or corroded reinforcing bars has been systematically studied since the 1990s [163–169]. The ductility of the columns will reduce even at low levels of corrosion, and the retrofitting measure with CFRP can increase the ductility but will not increase the lateral strength in [170]. Above all, it is obvious that corrosion attributed by chloride could result in a deterioration in the seismic performance of columns. These studies have demonstrated that using FRP sheets is very efficient in increasing the load-bearing capacity of columns and preventing harmful attacks from outside sources, such as water, chloride ions, and sulfate ions. This reduces the corrosion of bar and increases the service life of RC structures. Although seismic performance of corroded concrete columns and corroded RC columns retrofitted with FRP has been studied, the seismic performance of corroded RC columns retrofitted with BFRP is still lacking.

1.2.4 Seismic Performance of Beam-Column Joints Retrofitted with FRP

The beam-column joint designed as the critical region of RC structures suffers high shear stresses and large shear deformations during earthquake, which may result in the brittle failure after the reinforcing bars corroded [19]. Results reported in

[171] indicate that the damaged characteristics of corroded beam-column joints can be evaluated by the acoustic emission technique, and the initial diagonal cracks of corroded specimens occur earlier than those of reference specimen. Tendency of b-values obtained from the acoustic emission of corroded specimens is more stable than that of reference specimen, which indicates that more microcracks and the reappearance of old cracks occur with the decrease of the load-bearing capacity. Indeed, the load-bearing capacity of corroded RC beams [145], columns [172], and shear walls [46] can be increased by repairing with BFRP and together with the seismic behavior of pre-damaged beam-column joints [173] can also be improved.

The seismic behavior of RC members also decreased after the earthquake damage, especially the beam-column joints, while investigations on the damaged joints retrofitted with BFRP were still limited. In recent times, frequent earthquakes have provoked considerable damages to RC structures or buildings [174]. These buildings, built in the 1960s and 1970s, are insufficiently detailed and have some deficiencies, such as deficient structural system or seismic design, low concrete strength, and unsatisfiable meeting requirements, which will cause those buildings to vulnerably experience considerable damages under the earthquake [175]. As mentioned, the beam-column joints are the momentous parts and suffer severely inelastic deformations in the earthquake [176–178]. Phenomena from the 1999 Kocaeli and Chi-Chi earthquakes exhibit brittle failures in the joints, which may lead to the collapse of whole buildings [179]. Cracks are significantly found at the surfaces of the column with the yielded longitudinal reinforcements of the beams penetrating the core area, which contributes to the degradation of the strength and ductility of joints [180]. Although BFRP and other FRPs sheets have been applied in retrofitting the seismic-damaged beams [181, 182] and columns [183, 184], assessments on the seismic-damaged beam-column joints retrofitted with BFRP are still limited.

1.2.5 Seismic Performance of Shear Walls Retrofitted with FRP

Investigations on the behavior of RC members with externally bonded FRP sheets have mainly concentrated on either CFRP or GFRP in last decades. Two key issues had a considerable influence on seismic performance of strengthened walls, involving the configuration of FRP strips and anchor system between FRP strips and concrete surface. X-shaped, U-shaped, lateral and parallel or combination of them are widely adopted in [185–189]. Results reported in [189] show that the best performance for the improvement of lateral displacement resistance capacity and load-bearing capacity of RC shear walls has been obtained from the strengthening with lateral strips. At present, epoxy was used to bond FRP materials to the exterior surface of concrete; however, it was commonly reported that the FRP strips debond from the surface prior to fracture under cyclic loads. Despite FRPs' high ultimate strength, structures strengthened with FRPs could be failed in a brittle manner potentially below its mechanical properties due to a bonding problem at the surface between FRP sheets and concrete. In this case, the FRP materials did not play the most important role in strengthening RC structures and it was a waste of material to some extent. To enhance the bond behavior between FRP materials and concrete effectively, anchor systems including steel plate anchor [186], U-shaped FRP and bonded metal anchor [187, 188], fan type anchor [189], and improved hybrid bonded FRP anchor [190] are widely used. Experimental results show that as results of prevention of debonding of FRP strips totally by the anchors, the tensile forces of the strips are provided the load-bearing capacity to continue till reaching considerable lateral displacement [189]. The flexibility of FRP materials has been fully studied.

Investigations on BFRP in retrofitting RC beams and columns have been conducted; however, investigations on seismic performance of corroded RC shear walls after repairing with BFRP sheets are comparatively limited.

1.2.6 Bond Behavior Between FRP Bars and Concrete

The bond strength between FRP bars and concrete is influenced by bar diameter [191, 192]. The bond strength between concrete and GFRP bars with diameter of 12.7 and 19.1 mm is experimentally investigated using a pull-out test [191], which shows that the bond strength decreases with the increase of bar diameter. A similar test on the bond strength between CFRP, GFRP, AFRP bars with different diameters and concrete is conducted in [192]. Although the effect of bar diameter on the bond strength between CFRP, GFRP, and AFRP bars and concrete has been investigated, the effect of bar diameter on the bond strength between BFRP bars and concrete remains lacking. Thus, whether and how the bar diameter influences the bond strength between BFRP bars and concrete need to be studied for better understanding the bond performance. The bond strength between FRP bars and concrete is also influenced by concrete strength [193]. Experimental results in [194] show that the bond strength between FRP bars and concrete is directly proportional to the concrete strength up to 20 MPa because bond failure is entirely due to the concrete crushing for low concrete strength. However, the effect of concrete strength on the bond strength and bond failure between BFRP bars and concrete remains lacking. Thus, the investigation on the effect of concrete strength on the bond strength and bond failure between BFRP bars and concrete needs to be studied further. The relationship between FRP bars and concrete is necessary to evaluate the load-bearing capacity of concrete components or structures reinforced with FRP bars. Experimental and theoretical investigations on the bond performance between FRP bars and concrete have been conducted in [192, 195], which suggest that the geometrical and mechanical parameters of FRP bars influence the bond behavior, and sometimes various parameters cause the complexity in determining the actual bond stress-slip relationship between FRP bars and concrete. The bond stress-slip relationships between FRP bars and concrete are presented based on range of slip [196]. Another bond stress-slip relationship for recycle aggregate concrete and bars was proposed in consideration of maximum bond stress and corresponding slip [197]. Although some models for bond stress-slip relationship between some FRP bars or reinforcing bars and concrete are proposed, the model for BFRP bars remains lacking. Thus, the model for bond stress-slip relationship between BFRP bars and concrete needs to be studied.

Dynamic loading, such as earthquake, blast, traffic loading, wind loading, and machinery, is inevitable for concrete structures during their service life [198–200]. The bond behavior of concrete members reinforced with FRP bars under dynamic loading is essential for evaluating the load-bearing capacity [201]. The strain rate is a factor that influences the bond strength of concrete members reinforced with FRP bars. Results in [202] show that the stiffness of stress-strain relationship curves of concrete in direct compression and tension increases as the strain rates increase. Results in [203] show that the strain rate has a pronounced influence on the bond strength of concrete members reinforced with deformed bars, and the higher the strain rate is, the greater the bond strength and the bond stiffness are. Result in [204] shows that the bond strength of GFRP sheet-concrete interface under dynamic loading is larger than the corresponding static value. However, investigations on the influence of strain rate on the bond strength of concrete members reinforced with BFRP bars are still lacking. The bond behavior of RC members is also determined by the slip corresponding to bond strength. A constant value is utilized for evaluating the slip corresponding to bond strength [205], which compares reasonably well with the results reported in [206]. However, a variable value 0.04 times bar diameter is utilized as the slip corresponding to bond strength [207]. Results in [208, 209] show that the value of the slip corresponding to bond strength is related to the clear distance between the lugs of reinforcing bars. However, investigation on the influence of strain rate on the slip corresponding to bond strength of concrete members reinforced with BFRP bars is still lacking. The bond stress-slip relationship model of concrete members reinforced with BFRP bars considering strain rate is of fundamental importance to better understand the bond behavior of concrete members reinforced with BFRP bars under dynamic loading. Thus, investigations on the bond stress-slip relationship of concrete members reinforced with BFRP bars under different strain rates need to be conducted.

Under severe seismic excitation, cyclic loading can cause bond deterioration between reinforcing bars and concrete [210] while the hysteretic behavior of concrete structures is highly dependent on the bond behavior between reinforcing bars and concrete. Investigations on the bond behavior between concrete and steel bars [205, 211–213], GFRP bars [214, 215], CFRP bars [215, 216], and FRP sheets [185] have been conducted under cyclic loading. The results in [217] show that the bond stress-slip relationship under cyclic loading between reinforcing bars and concrete is similar to that under monotonic loading while the slip corresponding to bond strength under cyclic loading is larger than that under monotonic loading. The results in [216] show that the bond strength of CFRP bars under cyclic loading is lower than that under monotonic loading. The results in [211] show that the slip at the loaded end and residual slip increase with the increase in the number of cycles, and the bond strength is not affected by repeated loading, providing that bond failure does not occur. The results in [212] show that bond behavior between reinforcing bars and concrete deteriorates gradually with the increase of number of cycles, and the deteriorative speed slows down with the increase of number of cycles. Although the bond behavior between concrete and reinforcing bars, GFRP bars, CFRP bars, and FRP sheets under cyclic loading has been investigated, the bond behavior between BFRP bars and concrete under cyclic loading remains lacking. Therefore, the effect of cyclic loading on the bond strength, the slip corresponding to bond strength, and the hysteretic curve area between BFRP bars and concrete need to be investigated to further understand the bond behavior.

1.3 Objectives and Scope

The authors presented systematically their experimental and theoretical researches on the seismic performance of corroded RC structures retrofitted with FRP in recent years in this monograph. Seven chapters were organized in this monograph, and the main contents were introduced briefly as follows.

Chapter 2 investigated the bond behavior between BFRP sheets and concrete under static, dynamic, and initial static loading. The dynamic effective bond length, dynamic bond stress, dynamic ultimate load, and dynamic local bond-slip relationship between BFRP sheets and concrete under different strain rates or initial static loading proportion were studied. Besides, the models for the dynamic ultimate load, bond stress, slip, effective bond length, and the bond stress-slip relationship between BFRP sheets and concrete were proposed in consideration of the strain rate or initial static loading.

Chapter 3 investigated the fundamental natural frequency of deteriorated RC box beam with initial flexural cracks and performance of deteriorated RC box beams retrofitted with BFRP sheets by three types of anchorage, such as U-strips anchorage, end anchorage with grooving, and steel plate anchorage. The failure mode, ductility, stiffness, load-bearing capacity, and fundamental natural frequency of deteriorated RC box beams without retrofitting or retrofitted with BFRP sheets were analyzed.

Chapter 4 investigated the seismic performance of corroded RC columns without retrofitting or retrofitted with BFRP sheets. The failure mode, stiffness, displacement ductility ratios, and cumulative energy dissipation of corroded RC columns without retrofitting or retrofitted with BFRP sheets were discussed. Besides, the corresponding results were also compared with those of corroded RC columns.

Chapter 5 investigated the seismic performance of corroded RC beam-column joints, corroded joints retrofitted with BFRPs, earthquake-damaged and corrosion-damaged joints retrofitted with BFRPs, uncorroded joints strengthened with BFRPs in five types. The failure mode, load-bearing capacity, stiffness, ultimate rotations, displacement ductility ratios, and cumulative energy dissipation were analyzed. The models for shear strength of core area of joints in consideration of corrosion rate, earthquake damage, and FRP confinement were proposed.

Chapter 6 investigated the seismic performance of corroded RC shear walls, corroded walls retrofitted with BFRPs, and uncorroded walls strengthened with

BFRPs in fan anchor technique. The failure mode, yielding strength, ultimate shear strength, and cumulative energy dissipation were discussed. The models for the ultimate shear strength of corroded RC shear walls without retrofitting or retrofitted with BFRP sheets based on Strut-and-Tie model were proposed in consideration of corrosion rate as well as FRP confinement.

Chapter 7 investigated the bond behavior between BFRP bars and concrete under static, dynamic, and cyclic loadings. Firstly, the bond stress-slip relationship between BFRP bars and concrete under static loading was investigated considering the ratio of concrete cover depth to diameter of BFRP bars and concrete cubic compressive strength. The bond strength and the slip corresponding to the bond strength were investigated considering the BFRP bar diameter, and the mechanisms of the bond failure between BFRP bars and concrete were revealed. Secondly, the bond behavior between concrete and BFRP bars under dynamic loadings was investigated. The models for the bond stress-slip relationship, bond strength, and the slip corresponding to the bond strength were proposed in consideration of the strain rate. Thirdly, the bond behavior between BFRP bars and concrete under cyclic loading was investigated, and the models for the bond strength, slip corresponding to bond strength, and hysteretic curve area were proposed considering the number of cycles.

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