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FOREFRONT PERSPECTIVE

Mechanism and control of the long-term performance evolution of structures

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ABSTRACT It is well known that structural properties degrade under long-term environmental exposure and loading and that the degradation rate is controlled by inherent physical and chemical degradation mechanisms. The elucidation of the degradation mechanisms and the realization of effective long-term performance degradation control have been a research frontier in the field of civil engineering in recent years. Currently, the major topics that concern this research frontier include revealing the physical and chemical mechanisms of structural performance evolution under long-term environmental exposure and loading and developing structural performance degradation control technologies based on fiber-reinforced materials, for example, fiber-reinforced polymers (FRPs) and fabric-reinforced cementitious matrix (FRCM). In addition, there are novel structural performance control technologies, such as using a shape memory alloy (SMA) and self-healing concrete. This paper presents a brief state-of-the-art review of this topic, and it is expected to provide a reference for subsequent research.

KEYWORDS degradation mechanism, performance evaluation strengthening, FRP, FRCM

1 Introduction

Engineering structures will inevitably suffer from performance degradation due to environmental exposure and mechanical loads during their service life. To fully understand the life cycle performance of a structure, it is necessary to investigate its inherent damage evolution mechanism and to conduct long-term performance prediction research. Currently, from the perspective of physics and chemistry, the inherent degradation mechanisms of engineering materials (e.g., carbon steel bars, concrete, structural steel, composite materials) under differing loads and environments have been studied. Then, many predictive models for long-term performance evolution of structures have been established. On this basis, performance strengthening and repairing technologies for damaged structures have been established to improve the reliability of structures and the effective control of structural performance.

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Currently, major research topics that concern the mechanism and control of the long-term performance evolution of structures include the following. 1) Establishing evaluation and prediction models for the long-term performance of structures based on obtained performance degradation data from engineering materials. Then, choosing a proper maintenance program based on the reliability assessment results. 2) Developing technical systems for the improvement and control of the structural performance with novel fiber-reinforced polymers (FRPs) and fabric-reinforced cementitious matrix (FRCM) materials. 3) Other novel technical approaches that incorporate advanced materials, such as shape memory alloys (SMAs) and self-healing concrete, for the control of structure performance degradation.

2 Performance degradation mechanisms and prediction models

A contribution will be made to the adoption of economically reasonable performance degradation control technology (i.e., a suitable maintenance program) if the inherent physical and chemical mechanisms of structural performance degradation can be clearly revealed. As shown in Fig. 1, first, based on accelerated durability tests in the laboratory and/or on long-term on-site observations, the degradation mechanism of engineering structures at the material and interface bonding levels can be revealed, and then, it is possible to establish evaluation and prediction models for the long-term performance of structures. Finally, based on those prediction models, the design of a performance maintenance program can be conducted by combining reliability analysis theory with existing strengthening technologies.

2.1 Performance degradation mechanism

Steel bar reinforced concrete (RC) structures, steel structures and masonry structures are the three most common types of structures in civil engineering. For RC structures, the deterioration of the concrete itself and the corrosion of the inner steel bars will alter the bond condition between the steel and the concrete, which will significantly reduce the serviceability and even the ultimate load capacity of RC structures. For steel structures, degradation is mainly caused by the corrosion of the steel, and the damage caused by local corrosion is more serious. For masonry structures, the mechanical properties of the bricks themselves and the mortar between the bricks will degrade under adverse environments, such as long-term freeze-thaw cycles, salt corrosion and groundwater migration. The methods used to measure structural performance deterioration, at present, are mainly divided into the following types: durability tests (e.g., accelerated corrosion and carbonation) [1,2], fatigue tests [3], long-term on-site observations [4], and smart structural health monitoring [5]. Through the measurement methods mentioned above, the degradation mechanism of the structure can be revealed.

2.2 Performance prediction models

In fact, structural performance degradation is a long-term process in real engineering systems [6]. However, combined with the revealed mechanism, the established long-term performance prediction models, which are normally obtained from regression analysis of experimental data through accelerated tests, can provide a feasible method to predict and evaluate the long-term behavior of structures. It should be emphasized that the accuracy of the prediction results must be checked against the long-term degradation data in the natural service environment. At present, the commonly-used prediction models proposed by previous researchers include the freeze-thaw cycle degradation model [7], the bond-slip deterioration model [8], the chloride-induced corrosion probabilistic model [9], and the prediction model of concrete carbonation depth [2].

3 Maintenance program design

Any newly built and/or retrofitted structure (or structural component) will gradually deteriorate during its anticipated service life depending on its environmental conditions, material properties and loading conditions [10,11]. As shown in Fig. 2, performance maintenance actions are always needed when the performance reliability approaches its safety threshold [12]. Reliability analysis based on predicted degradation models is helpful for determining when and where maintenance practices should be performed and for providing useful information on the best choices for specific retrofitting measures [13,14]. The life-cycle performance index of a typical structure is conceptually illustrated in Fig. 2. When the structural performance index decreases over time due to, for example, corrosion and fatigue, the expected maintenance (e.g., using FRPs or FRCM) will be needed to increase the performance level of the structure (the performance index increase is shown in Fig. 2). As shown in Fig. 2, after an unstrengthened structure is first retrofitted, its performance index will still decline with service time. Therefore, it is also necessary to study the long-term performance evolution law of the retrofitted structures, and if necessary, a second or even third maintenance will be needed.

4 Structure performance control technology based on FRP materials

FRP is made of a continuous fiber and polymer matrix by

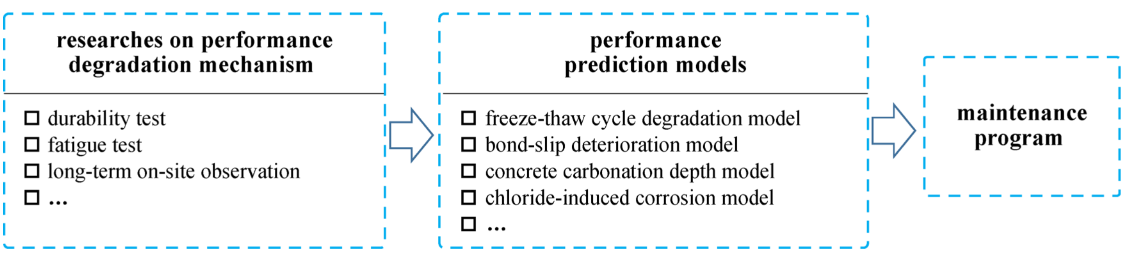

Fig. 1 Flowchart of the overall research method for long-term performance control.

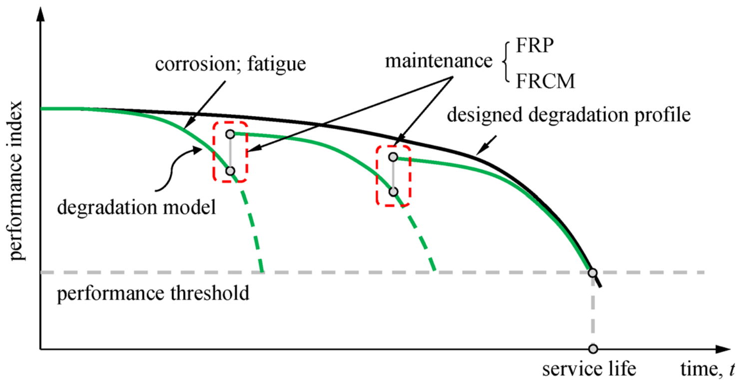

Fig. 2 Schematic diagrams of the effect of the maintenance on structural performance.

special manufacturing techniques in civil engineering (Fig. 3). Carbon fiber, glass fiber, basalt fiber, and aramid fiber are the most commonly used fiber types [15]. Consequently, FRP products usually include carbon FRP (CFRP), glass FRP (GFRP), basalt FRP (BFRP), and aramid FRP (AFRP) depending on the fiber type adopted. Compared with concrete and structural steel, FRP materials have some distinct advantages, such as being lightweight and having high strength, high corrosion resistance, and excellent fatigue resistance. It should be noted that the different FRP types differ in tensile strength and elastic modulus due to the different fiber types used in FRP composites. However, all of the different FRP types are linear-elastic, and thus, ductility must be considered when a FRP is used to improve and control structural behavior. Because of these unique properties, the study of the improvement and control of structures based on FRP composites has become a research hotspot in civil engineering over the past three decades.

Among the existing techniques, the externally bonded (EB) FRP strengthening technique was the first technique applied and is the most studied in the field of structural strengthening. Especially after the Hyogoken-Nanbu Earthquake, successful applications of the EB-FRP strengthening technique for strengthening concrete structures greatly promoted its study and application and made it a popular strengthening technique [15]. Based on many studies and engineering applications, some design guidelines and code have been established to guide applications of the EB-FRP strengthening technique [16–18]. In 2011, the technical code for infrastructure applications of FRP composites in China was implemented, in which the design methods for the EB-FRP system for strengthening concrete structures and masonry structures were specified [19]. In addition, with the development of relevant research, many other types of FRP products, such as FRP bars, FRP grids, FRP pultruded profiles and FRP cables, have also been developed to enrich the applications of FRP in civil engineering (Fig. 3(b)). Researchers and engineers have also developed and studied the near-surface mounted (NSM)-FRP strengthening technique, the externally prestressed FRP strengthening technique and some combined strengthening techniques with different FRP products [20–24]. Research and applications for FRP strengthening have also been extended from concrete structures to steel structures, masonry structures and timber structures [25–31].

4.1 EB-FRP strengthening system

As shown in Fig. 4, the EB-FRP technique has been studied and applied extensively for enhancing and controlling structural performance. The EB-FRP technique is usually used by bonding or wrapping FRP on structural surfaces [32]. Studies have proved that the flexural and shear capacity of concrete structures can be significantly increased with the EB-FRP system [33,34]. Furthermore, if the EB-FRP is prestressed, the stiffness of structures can be enhanced in such a way that the deflection and crack width can be effectively controlled while the capacity is increased [35,36]. By wrapping FRP around concrete columns, their seismic behavior and ductility can be improved due to the lateral confinement effect [37]. The shear capacity and seismic behavior of masonry structures can also be enhanced by using the EB-FRP system [25,27]. In addition, studies have indicated that the use of the EB-FRP system can improve the tension capacity, flexural capacity, anti-buckling capacity and, especially, the fatigue behavior of steel structures [38–41]. Moreover, crack initiation and propagation in steel structures can be completely arrested by using a prestressed EB-FRP plate [42].

4.2 NSM FRP strengthening system

The NSM-FRP technique is another type of strengthening system that has received widespread attention in recent years. As shown in Fig. 5(a), FRP rods/FRP strips are bonded into grooves that were cut into the surface of the concrete, with the appropriate adhesive (typically an

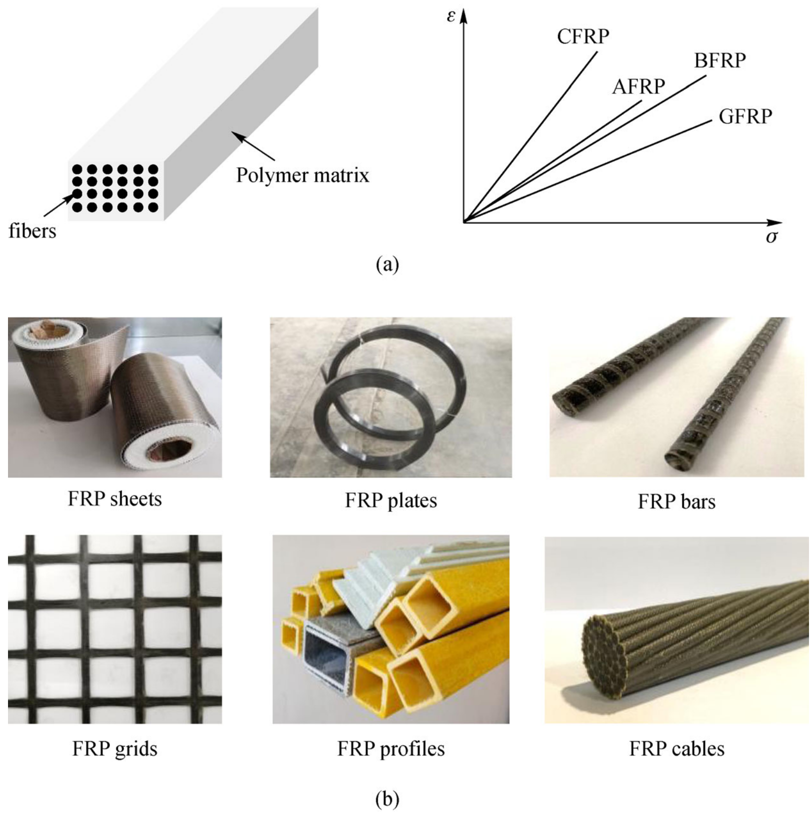

Fig. 3 FRP materials and mechanical properties. (a) FRP composition and mechanical properties; (b) typical FRP products.

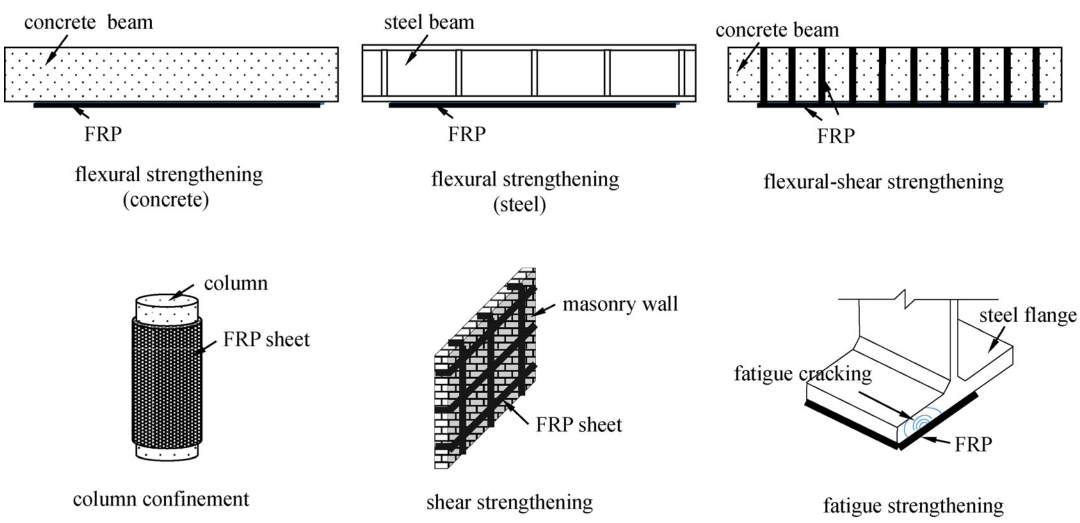

Fig. 4 Typical EB-FRP strengthening system.

epoxy) [43]. As shown in Fig. 5(b) and Fig. 5(c), the bending resistance capacity [44,45] and the shear bearing capacity [46,47] of the concrete members can be improved by embedding FRP reinforcements into the surface grooves. Currently, most adhesive materials filled in grooves are organic-based epoxy adhesives. A few studies have used cementitious materials as groove filling materials. Additionally, because FRP materials are embedded in grooves, the fire resistance performance of a structures strengthened with the NSM-FRP system is better than those strengthened with the EB-FRP system [48,49], and research has confirmed that it is better to adopt

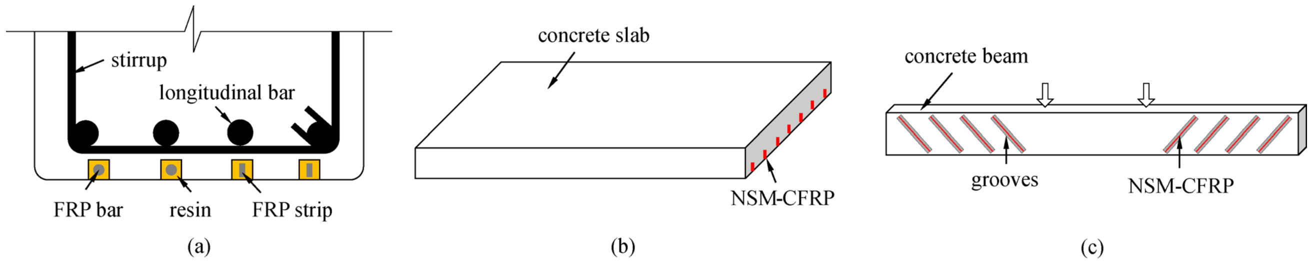

Fig. 5 Typical NSM-FRP strengthening systems. (a) Schematic diagram; (b) flexural; (c) shear strengthening.

inorganic adhesives as the groove filling material than epoxy adhesives in a fire environment [50].

4.3 External strengthening with FRP tendons

Because of their lightweight, high strength and corrosion resistance properties, FRP tendons are also used in the field of externally prestressed strengthening. When used for external strengthening, the anchoring and steering of the FRP tendons are the critical issues. Currently, focusing on the anchorage system and the deviator, which have significant effects on the mechanical behaviors of external FRP tendons, special wedge anchors have developed [51] (Fig. 6(a)), and the deviator radius of bent FRP tendons has been optimized [52] (Fig. 6(b)). As shown in Fig. 6(c), the structural performance of beams that were externally prestressed by CFRP tendons was similar to that of those prestressed by steel tendons [53,54]. Critical parameters, such as the tendon profile (straight or deviated), the strength of the concrete, the effective tendon depth, and the number of deviators, must be considered when calculating the ultimate stress in the external tendons [55].

5 Structure performance control technology based on FRCM materials

The use of FRCM composites as strengthening materials to control the performance degradation of structures is a new emerging technology based on fiber-reinforced composites. The FRCM composites shown in Fig. 7 are comprised of high-strength fabric grids applied to a substrate through an inorganic cementitious matrix. The cementitious matrix used in the FRCM composites has a higher thermal capacity and better compatibility with the concrete and masonry substrate than the organic resin used in FRP [56–59]. In addition, compared with the linear elasticity failure of the FRP, the tensile stress-strain curve of the FRCM is typical bilinear due to the generation of dispersed cracks.

5.1 FRCM RC structures

Figure 8 shows some major research fields of FRCM RC structures, which include bond behavior testing with concrete substrates by single-lap shear tests and double-

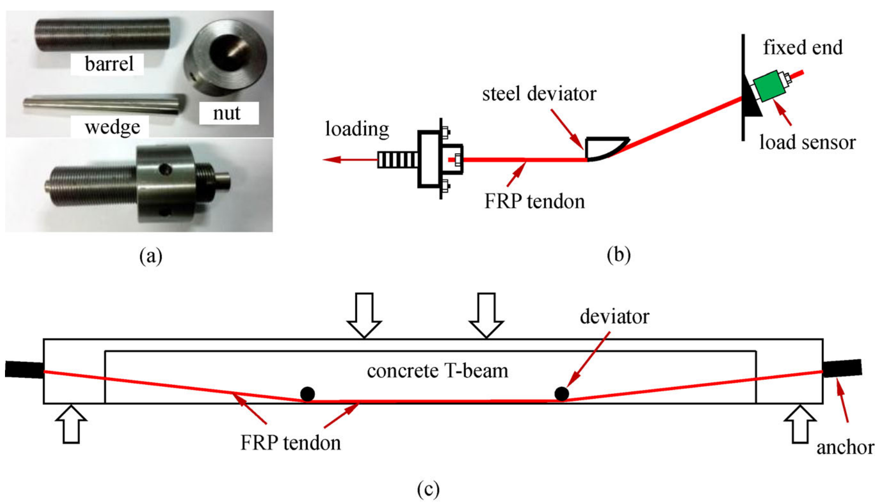

Fig. 6 Typical systems of strengthening with externally prestressed FRP tendons. (a) Anchorage system; (b) deviator; (c) externally flexural strengthening.

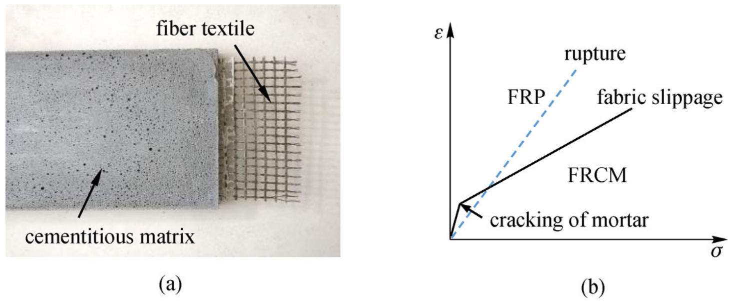

Fig. 7 FRCM materials and their mechanical properties. (a) FRCM; (b) stress-strain response.

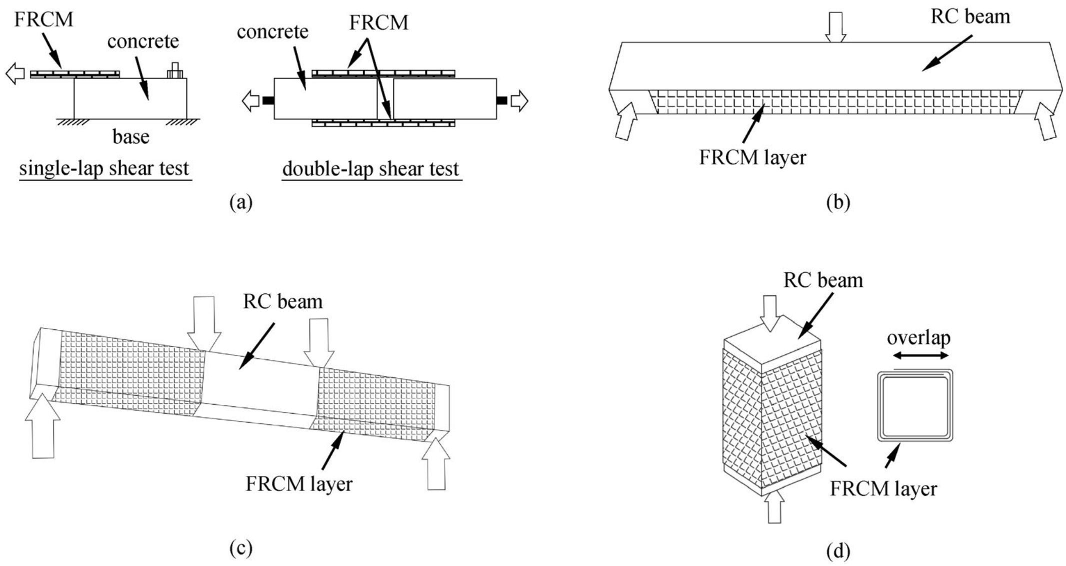

Fig. 8 Research on the strengthening of concrete structures with FRCM. (a) Bond behavior; (b) flexural strengthening; (c) shear strengthening; (d) column confinement. (reproduced from Ref. [57])

lap shear tests [60], flexural strengthening by bonding FRCM to the bottom of the concrete members [59,61], shear strengthening by wrapping FRCM in the shear span of concrete members [62,63], and improvement of the axial compression performance by cyclic wrapping the FRCM around concrete columns [64,65]. In addition, a few studies have compared the effectiveness of FRCM and FRP in strengthening concrete beams at room temperature and high temperatures [66,67]. Overall, it has been confirmed that FRCM materials have good effects and applications prospects for strengthening concrete structures.

5.2 FRCM reinforced masonry structures

Since the use of a cementitious mortar as an FRCM, which offers excellent compatibility with substrates, lower costs, and better performance at high temperatures, while enhancing permeability and achieving reversibility [68], FRCM has gained considerable popularity for strengthening masonry structures. As shown in Fig. 9, research is currently mainly focused on three areas, namely, in-plane strengthening, out-of-plane strengthening, and strengthening of arches [68,69]. FRCM-based strengthening of masonry walls subjected to out-of-plane and in-plane cyclic loads has been studied experimentally by Papanicolaou et al. [70,71] and Kariou et al. [72]. FRCM has also been used to strengthen masonry arch structures, and it was found that the collapse mechanism associated with the formation of hinges can be prevented by bonding FRCM to the extrados or the intrados of the masonry arch [73–75].

6 Future research topics

With the interdisciplinary development of materials science and engineering technology, an increasing number of new materials and technologies will be used in the

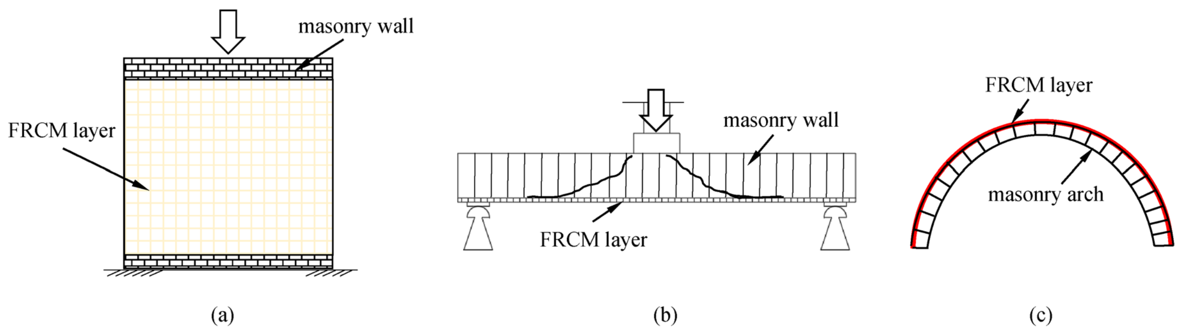

Fig. 9 Research on the strengthening of masonry structures with FRCM. (a) In-plane strengthening; (b) out-of-plane strengthening; (c) strengthening of arches.

control of structural performance. Recently, a series of strengthening technologies based on the SMA have been developed. Examples are strengthening RC beams with prestressed NSM-SMA [76], flexural strengthening structural concrete with EB-SMA strips [77], and strengthening steel plates with the iron-based SMA (Fe-SMA) [78]. It is expected that in the near future, research on the use of cost-effective Fe-SMA in intelligent structure performance control will be a hot spot. In addition, the application of nanotechnology to develop new concrete materials with unique mechanical and electrical properties will be another research frontier and hot spot. Advanced cement-based composites are very helpful for the efficient control of structural properties [79,80]. Furthermore, self-healing concrete developed using microbial technology, which can self-heal the cracks formed during service, will also be a promising research topic for the future intelligent maintenance of structures [81–83].

7 Conclusions

This paper gives a brief overview of research that concerns structural performance degradation mechanisms and strengthening technologies (using FRP and FRCM materials). In addition, the hotspots of future research are also described. In general, the future of structural retrofitting will be more durable, more efficient and more intelligent, including a clearer understanding of the mechanism of structural deterioration and the use of more intelligent materials.

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