Review Article

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Interfacial technology for enhancement in steel fiber reinforced cementitious composite from nano to macroscale

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Abstract: The rapid construction of innovative structures and megastructures is pushing the development of steel fiber reinforced cementitious composite (SFRCC). The interfacial enhancement technology from nano to macroscale for improving global properties of SFRCC is summarized here, including nanomaterials reinforcement of cementitious matrix, physical arrangement and nanomaterials modification of steel fiber. The interfacial bonding strength of SFRCC can be enhanced more than 150% *via* these approaches. To evaluate the effect of local interfacial technology on global mechanical properties of SFRCC, the structural performance of SFRCC with interfacial modification is reviewed. The energy absorption capacity of SFRCC can be improved over 20% through interfacial enhancement technology. The multi-scale mechanisms behind these approaches are illustrated through macroscale characterizations and molecular dynamics modeling. Furthermore, the key challenges and future prospects of enhancement approaches are also discussed from the perspectives of bottom-up system, nanoscale reinforcement, and durability properties in SFRCC, which are expected to inspire further improvement in interfacial performance and promote the application of SFRCC in practical engineering.

Keywords: interfacial enhancement, physical treatment, nanomaterials modification, fiber reinforced cementitious composite, multi-scale mechanisms

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1 Introduction

During the past few decades, one important demand of construction community and industry is to exploit and apply the innovative structures and megastructures, including long-span bridges, high-rise buildings, super thin-walled shells, and protective equipment [1,2]. Conventional concrete cannot satisfy the requirements of aforementioned structures due to its poor bending and tensile performance [3]. Extensive studies have been conducted to develop advanced construction materials with outstanding mechanical properties [4,5]. Fiber reinforced cementitious composites belong to the representative of advanced cementitious materials, and the commonly employed fibers are polyvinyl alcohol fibers, polyethylene fibers, carbon fibers, basalt fibers, and steel fibers [6,7]. Among these fibers, steel fibers exhibit superior tensile strength and stiffness, which can significantly enhance the mechanical performance of cementitious composite materials [8,9]. Steel fiber reinforced cementitious composite (SFRCC) is characterized with both desirable compressive and tensile performance, which has attracted great attentions and interests in the past few years [10,11]. In general, the raw materials of SFRCC include cement, silica fume, quartz or river sand, superplasticizer, and steel fibers [12]. Ultra-high performance concrete, which belongs to a kind of SFRCC, owns the superior compressive strength more than 150 MPa and flexural strength over 30 MPa [13]. Such performance offers great potential to fabricate lighter and thinner section for structural application [14]. The MuCEM museum in France was built in 2013, and it shows an elegant, delicate, and slender appearance due to the flexible architectural and strong structural properties of SFRCC. The Hutong Yangtze river bridge in China was built in 2020, which is the world's first road–rail bridge with a span of more than 1 km. The bridge deck is constructed of steel-SFRCC composite material, and the bending stiffness of bridge deck improved by 30 times due to the use of SFRCC. Based on SFRCC, the building of different innovative structures and megastructures is within the bounds of possibility.

The mechanical properties of fiber reinforced cementitious composites are closely related to the interfacial performance between fiber and cementitious matrix [15,16]. The role and function of the interfacial performance for SFRCC under tension are illustrated in Figure 1. The interfacial performance governs the stress transfer from cementitious matrix to fiber, which in turn controls the crack initiation and propagation [17]. The ability of crack controlling is a key index for evaluating the tensile and flexural performance of cementitious material [18,19]. The multiple microcracks and high energy absorption capacity of cementitious material can be obtained with satisfactory ability of crack controlling [20,21]. However, the single crack failure mode of SFRCC is often observed under tension, and the brittle failure mode is still emerged when subjected to high strain rate of dynamic load [22]. The brittle failure of structures may lead to catastrophic collapse and pose serious threats to the human safety and property [23]. Therefore, tailoring the interfacial performance of SFRCC is an important issue. With the improvement in interface between fiber and matrix, the cracks can be significantly reduced in terms of amount and width when the elements are subjected to extreme loads [24,25]. Moreover, the durability of SFRCC can be improved with the well-controlled cracks and permeability. In this situation, the catastrophic collapse of structures can be avoided and the maintenance of structures can be decreased, which can save a great deal of manpower and material resources. Hence, the breakthroughs in enhancing the interfacial performance are expected to contribute to the development of SFRCC.

The technologies for interfacial performance enhancement have been developed mainly from the perspectives of cementitious matrix and steel fiber [26]. The properties of cementitious matrix refer to the microstructure and mechanical strength, and the properties of steel fiber include the shape and surface characteristic. The microstructure and mechanical strength of matrix play an important role on the performance of interfacial transition zone [27], which is the weakest region in SFRCC. The anchorage force at interface is governed by the shape of steel fibers, and various shapes of steel fibers have been adopted to improve interfacial performance [28,29]. The adhesion bond at interface is dominated by the surface characteristics of steel fibers, and different approaches have been proposed to modify steel fibers surface [30,31]. In recent years, various powder materials and fibers are covered to review the effect of raw materials on fiber reinforced cementitious composites [32,33]. The rheological properties, flexural performance, tensile behavior, dynamic response, and durability of fiber reinforced cementitious composites are discussed to review their global performance [34–36]. The utilization of fiber reinforced cementitious composites in bridge engineering, high-rise buildings, innovative structures, and protective equipment is presented to review their structural application [37,38]. Based on the above analyses, existing review literatures are mainly concentrated on the constitutive materials and global mechanical performance of fiber reinforced cementitious composites. However, the clear classification of interfacial enhancement approaches for SFRCC has not been established, and a fair comparison on the effectiveness of enhancement among different approaches is difficult to realize. Meanwhile, the enhancement in interfacial performance contributes to the desirable global mechanical properties of SFRCC, but the relationship between interfacial performance and global mechanical performance about the enhancement approaches is still not clear. Therefore, there is an urgent need to synthesize and analyze different kinds of interfacial enhancement approaches to reflect the current state of this field. A comprehensive review and

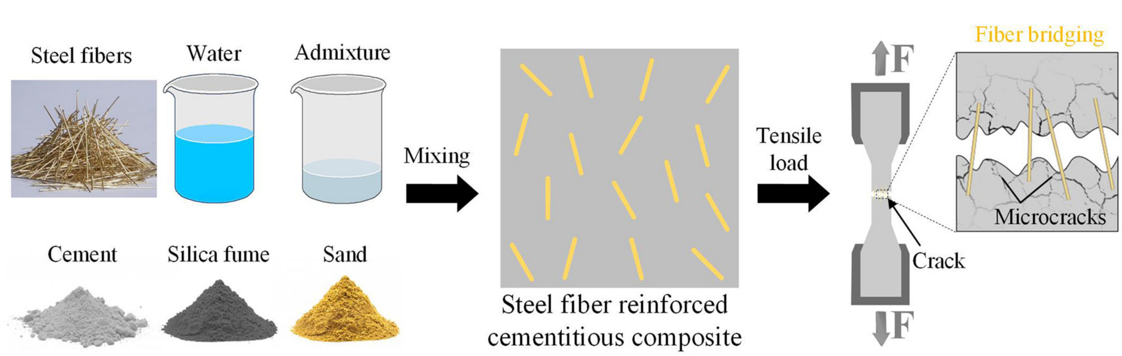

Figure 1: Schematic diagram of the bridging effect of steel fiber at interface under tensile load. The stress transfers from cementitious matrix to steel fiber at interface, which retards the initiation and propagation of cracks in SFRCC.

comparison of all the technologies for interfacial performance enhancement is necessary to overcome the existing limitations, and the effect of these technologies on the global mechanical performance needs to be summarized and analyzed.

The objectives of this paper are to systematically summarize the enhancement approaches for interfacial performance of SFRCC from nano to macroscale and to demonstrate its key challenges and future development trends. The interfacial modification approaches of SFRCC have been reviewed first in terms of mechanical improvement of cementitious matrix, physical arrangement of steel fiber, and chemical modification of fiber surface, with the working mechanisms of different methods being discussed. Furthermore, the structural performance of SFRCC with interfacial modification under various loading conditions has been discussed to illustrate the effectiveness of the enhancement approaches. The limitation of current interfacial modification approaches in SFRCC is discussed as well, with the future prospects being proposed to achieve the potential advancement of SFRCC in terms of mechanical enhancement and durability. It is envisioned that this paper can provide insightful viewpoints on knowledge basis and interfacial performance enhancement for SFRCC, which can further promote its application in innovative structures and megastructures.

2 Interfacial enhancement approaches

The interfacial bond properties of SFRCC are classified into two categories, *i.e.*, physicochemical and mechanical bond properties between steel fiber and cementitious matrix [39,40]. The physicochemical bond is influenced by adhesion and friction at the interface, while the mechanical bond is caused by anchorage effect at the fiber end or along the fiber [41]. The physicochemical bond works initially prior to mechanical bond at the interface in the stage of steel fiber debonding [42]. The coaction of physicochemical bond and mechanical bond can produce synergistic effect to resist steel fiber being pull out from cementitious matrix.

The investigations on the interfacial performance enhancement have been conducted from the perspective of mechanical and physicochemical bonds. The mechanical strength of matrix provides the circumferential compressive normal stress around fiber, which is a crucial factor in determining the friction at interface. The dense microstructure of matrix brings benefit to friction strength at interface, and the geometric deformation of steel fiber contributes to strong anchorage force at interface. Meanwhile, the hydrophobic nature of steel fiber surface leads to the formation of weak physicochemical bond at interface and further weakening the pullout resistance of steel fibers from cementitious matrix [43]. The introduction of new functional groups to steel fiber surface is a feasible method for changing its surface characteristic. The different chemical modification approaches, including zinc phosphate (ZnPh) treatment, silane coupling agent (SCA) treatment, plasma treatment, and nanomaterials coating, have been proposed to increase the fiber hydrophilicity and establish tight bonding at interface. All the above enhancement approaches are introduced and compared in Table 1.

2.1 Mechanical properties of cementitious matrix

As a multiphase construction material, SFRCC consists of binding phase (cement matrix), particulate phase (quartz or river sand), and steel fibers. The cementitious matrix is composed of binding phase and particulate phase. The mechanical strength and microstructure of cementitious matrix are the key factors for physicochemical bond, and the high mechanical strength and dense microstructure contribute to desirable interfacial performance [44,45]. The various approaches to enhance interfacial performance from the perspective of cementitious matrix are summarized in Table 1. In order to investigate the interfacial performance between fibers and the surrounding cementitious matrix, one common method is fiber pullout test [46,47]. The dog-bone specimen with embedded steel fibers was first fabricated. Then, the fiber pullout test was conducted with displacement control of 1 mm/min according to the Chinese Standard CECS13-2009 and related literatures [48]. The evaluation indexes for interfacial performance include pullout load, interfacial bonding strength, and pullout energy [49]. At the same embedded length, the pullout energy of steel fiber increased with the rise of cementitious matrix strength. When the matrix strength raised from 158 to 196 MPa, an increase of 34% upon pullout energy of steel fiber was obtained during fiber pullout test [50]. The water to binder ratio is correlated to the porosity and mechanical strength of cementitious matrix. The pullout load of steel fiber increased by 10–25% with the decrease of water to binder ratio from 0.4 to 0.2 [51,52]. It has been established that the curing regime can affect the microstructure

Table 1: Effect of various approaches on the interfacial performance enhancement of SFRCC

Approaches type	Variables	Performance improvement	Refs
Mechanical properties of cementitious matrix	Water to binder ratio	10–25% in pullout load	[51,52]
Mechanical properties of cementitious matrix	Autoclave curing and steam curing	85–110% in interfacial bonding strength	[53,54]
Mechanical properties of cementitious matrix	Content of silica fume	9–40% in interfacial bonding strength	[56,57]
Mechanical properties of cementitious matrix	Content of nanomaterials (nano-SiO_2, nano-$CaCO_3$ and nanoplatelets, *etc.*)	40–55% in interfacial bonding strength and 70–230% in pullout energy	[60,61]
Physical arrangement of steel fiber	Corrugated steel fiber	140–300% in interfacial bonding strength and 250–350% pullout energy	[29,62]
Physical arrangement of steel fiber	Hooked steel fiber	240–700% in interfacial bonding strength and 190–400% in pullout energy	[28,52]
Physical arrangement of steel fiber	Embedded length	30–50% in pullout load	[51,63]
Physical arrangement of steel fiber	Embedded angle	20–80% in interfacial bonding strength	[64,65]
Physical arrangement of steel fiber	Fibers distance	5–20% in interfacial bonding strength and 15–20% in pullout energy	[66]
Chemical modification of steel fiber surface	ZnPh coating	20–70% in pullout load	[30,67,68]
Chemical modification of steel fiber surface	SCA modification	35–75% in interfacial bonding strength and 20–85% in pullout energy	[69,70]
Chemical modification of steel fiber surface	Plasma treatment	20–30% in pullout load and 30–40% in pullout energy	[31,71]
Chemical modification of steel fiber surface	Nanomaterials coating (Nano-SiO_2, carbon nanofibers and nanographene, *etc.*)	70–80% in interfacial bonding strength and 60–70% in pullout energy	[49,72]

of SFRCC, and the optimum curing regime leads to remarkable reduction in porosity and permeability [53]. The standard curing temperature regime is 20 ± 2°C, and the humidity is equal or greater than 95%. Compared with the standard curing regime, the autoclave curing and steam curing regimes can significantly increase the interfacial performance; a maximum enhancement of 110% on interfacial bonding strength was achieved [54]. The reason is that the autoclave and steam curing regimes accelerate the hydration of cement and promote secondary hydration between mineral admixtures and calcium hydroxide [55]. Silica fume is characterized with fine particle size and high pozzolanic activity, which is conducive to densifying the cementitious matrix. Hence, the content of silica fume in cementitious matrix can cause a change of interfacial performance in SFRCC, and the optimum content of silica fume for interfacial bonding strength is between 15 and 25% [56,57]. Moreover, using nanomaterials as additives in SFRCC is an effective approach to improve the interfacial bonding between fiber and cementitious matrix, due to the filling and nucleation effects and chemical reactivity of nanomaterials, leading to dense microstructure and high mechanical strength [58,59]. The interfacial bonding strength and pullout energy of cementitious matrix with nano-SiO_2 improved by 43 and 74%, respectively, compared with the reference cementitious matrix [60]. The above findings reveal that the mechanical properties of cementitious matrix have an influence on physicochemical bond properties at interface, thereby bringing the variations in interfacial performance of SFRCC.

2.2 Physical properties of steel fiber

The physical properties of steel fiber, including fiber shape, fiber diameter, fiber embedded angle, fiber embedded length, and fiber distance, are the crucial factors for interfacial performance. Previous studies on the effect of physical factors on interfacial performance of SFRCC are summarized in Table 1. For the straight steel fiber, the friction at interface plays a significant role for the pullout resistance of steel fiber [26]. Compared to the straight steel fibers, the deformed fibers also generate the anchorage force at interface under the static loading conditions, as shown in Figure 2. The use of corrugated and hooked fibers can effectively enhance the interfacial performance in SFRCC [29,52,62]. The interfacial bonding strength and pullout energy of hooked fibers were approximately three and four times greater than those with straight fibers, respectively [28]. At the same length and diameter, the interfacial bonding strength and pullout energy of hooked fiber increased by 118 and 56%, respectively, relative to those of corrugated fiber [29]. The bonding area between fiber and cementitious matrix at the interface is affected by fiber diameter and fiber embedded length [51]. The increase in bonding area is beneficial to stress transfer at the interface, further improving the interfacial performance of SFRCC. When the embedded length of steel fiber increased from 10 to 40 mm, the enhancement in pullout load reaches to 30–50% during the fiber pullout test [73]. It should be noticed that the overlong fiber leads to poor fiber dispersion and fiber agglomeration, which cause the deterioration in mechanical performance [74]. The pullout behavior is also affected by various embedded angles of steel fiber in cementitious matrix. It has been reported that the interfacial bonding strength of straight fibers increased by about 20% when the fiber embedded angle rose from 0° to 30° [64,65]. In addition, the distance between steel fibers exhibits an effect on the interfacial performance, the interfacial bonding strength and pullout energy enhanced by 5–20% with the distance decreasing from 2.7 to 1.0 mm during fiber pullout test [66]. In summary, the effect of fiber shape, fiber diameter, fiber embedded angle, fiber embedded length, and fiber distance on the interfacial performance has been extensively studied. Among these factors, the change of fiber shape is regarded as the effective approach to significantly enhance the interfacial performance of SFRCC. However, the deformed steel fibers induce a negative effect on the workability of SFRCC, which is a drawback in field-casting projects. For SFRCC with deformed steel fibers, the optimization design between interfacial performance and workability should be determined in practical application.

The coupled effect of the enhancement approaches on interfacial performance of SFRCC has been explored [65], and the combination of deformed steel fiber and various embedded angle can effectively enhance the interfacial performance of SFRCC. The pullout load of hooked steel fiber with embedded angles of 45° improved by 110% compared with that of straight steel fiber with embedded angles of 0°.

2.3 Surface chemical modification for steel fiber

The surface characteristic of steel fiber is closely related to the physicochemical bond between steel fiber and cementitious matrix [75]. To prevent the corrosion of steel fibers in SFRCC, the copper plating on steel fiber surface is usually adopted. As the copper owns poor hydrophilicity and cementitious matrix contains water, the interfacial bond between steel fiber and cementitious matrix is relatively weak [76]. The weak bond at interface results in easy debonding during fiber pullout test. There is a crucial demand for increasing the hydrophilicity of steel fiber surface. The chemical modification could alter surface characteristics of steel fiber, which is proved to be

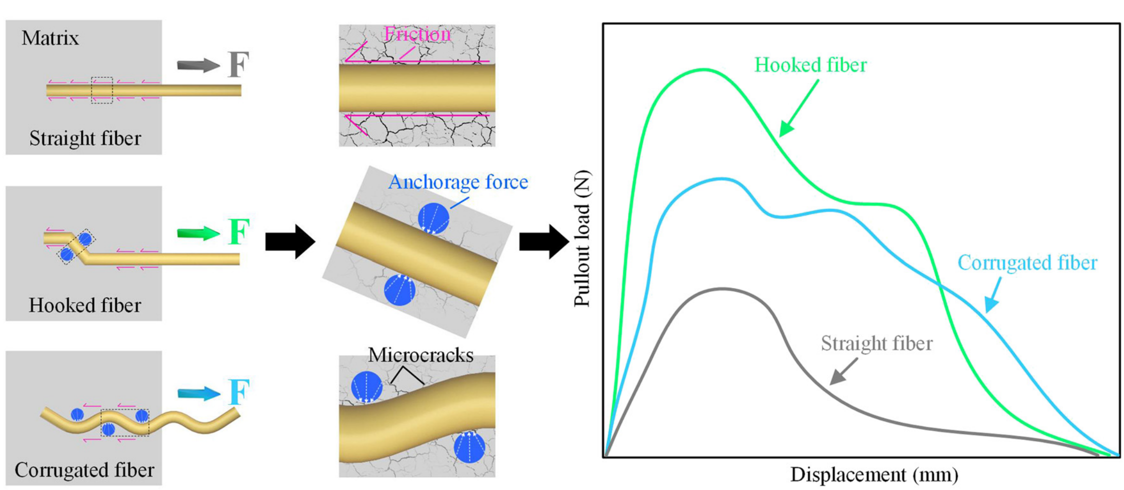

Figure 2: Pullout behavior of steel fiber with various shapes from SFRCC matrix. For the straight steel fiber, the friction at interface is the main resistance from fiber pullout. For the hooked and corrugated steel fiber, the anchorage force at interface plays a critical role to resist fiber pullout.

an effective approach to improve the interfacial bond [30,31,49,70]. The details of chemical modification approaches and the effect of these approaches on interfacial performance are displayed in Table 1. ZnPh conversion coating belongs to an inorganic crystalline coating that can strengthen the bond between steel fiber and cementitious matrix [30]. The coating process of ZnPh can be divided into two main procedures. The steel fibers are first washed with acetone solution to remove surface impurity. Then, the cleaned steel fibers are immersed in ZnPh solution at 80–90°C for 15 min. After that, the steel fibers rinsed with water and dried for 10 min at 150°C, and the ZnPh conversion coating of steel fibers is finished. An increase of 40% in the pullout load was recorded after ZnPh treatment of steel fiber [68]. Such improvement is attributed to the formation of hydroxyapatite and brushite at matrix–ZnPh coating interface [67]. Meanwhile, the increase in surface roughness caused by ZnPh film results in a larger friction between fiber and cementitious matrix, contributing to the enhanced interfacial performance. However, the ZnPh is classified as industrial pollutant according to the emission standards for inorganic chemical industry. The heavy metal ion (Zn) can damage the human skin and mucosa and impede crop growth, and the phosphorus (P) can pollute water and soil, threating the environment safety and human health. Such disadvantage limits its wide application in SFRCC for practical engineering.

As a nontoxic and non-pollution chemical agent, SCA can create a chemical bridge between two different materials and improve the interfacial performance [77,78]. Numerous investigations have been demonstrated that SCA can improve the bond performance at interface between nonmetallic fibers and cementitious matrix [79,80]. For the interfacial bond properties between metallic fibers (steel fibers) and cementitious matrix, the effect of SCA modified steel fibers on its performance has been investigated recently [69]. The SCA modification for steel fibers consists of two steps, *i.e.*, alkali pretreatment and SCA treatment. The steel fibers are first immersed in NaOH solution for 30 min to enhance their surface activity. After washed with water and ethyl alcohol absolute, the pretreated steel fibers are sprayed with SCA solution through a sprinkler. Next, the obtained steel fibers are dried in an oven at 120°C for 2 h and the modification of steel fibers is finished. It has been reported that the growth rates of interfacial bonding strength and pullout energy of steel fiber can reach 72 and 84% after SCA modification, respectively [70]. After alkali pretreatment, the high density of hydroxyl groups is introduced onto the steel fiber surface [81]. The reactive hydroxyl groups can react with SCA and generate chemical bond at interface [80]. Based on this principle, the SCA film is coated on the steel fiber surface by chemical bonding (Cu–O–Si groups). To reveal the enhancement mechanism of SCA modification, the morphology of steel fiber embedded in cementitious matrix is characterized. The nanoscale debonding process between the steel fiber outer layer and the cementitious matrix is explored using molecular dynamics (MD) simulation, as displayed in Figure 3. The interfacial zone is denser between the SCA modified steel fiber and the matrix. The separation between C–S–H and copper oxide is observed, while the interface between C–S–H and SCA molecules remains intact during the pulling process [70]. Such phenomenon indicates that the adhesion between C–S–H and the surface of copper oxide is weaker than that between

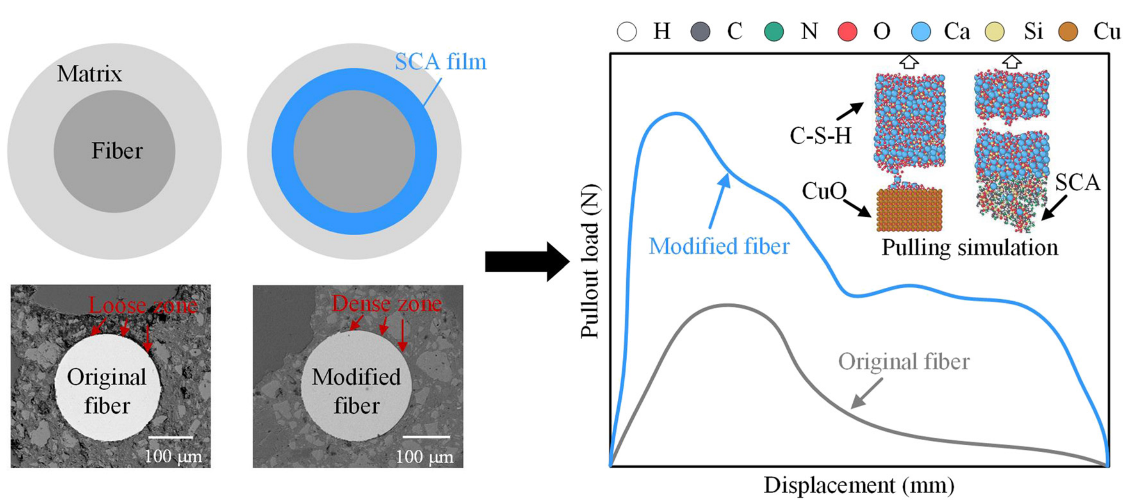

Figure 3: Morphology of original and modified fiber embedded in SFRCC matrix. The interfacial zone between SCA modified fiber and matrix is denser than that of original fiber and matrix, leading to a remarkable improvement in pullout load. MD simulation demonstrates that a tight bond is formed at interface after SCA modification.

C–S–H. In this situation, the SCA film acts as a “bonded bridge” that adheres the cementitious matrix to steel fiber tightly. Due to the non-pollution, low cost, and simple process characteristics of SCA modification, such effective approach can be widely adopted in SFRCC.

Plasma is a medium consisting of electrons and positively charged ions and it is regarded as the fourth state of matter [82]. Plasma treatment has been used extensively to induce chemical and physical changes on the surface of polyethylene, polypropylene, polyethylene terephthalate, and polyvinyl alcohol fibers [83]. The behind mechanism is that plasma treatment can remove surface contaminants and deposit functional groups on the fiber surface [84], which exhibits great potential for changing the surface characteristic of steel fiber. The application of plasma treatment to steel fibers has garnered significant interest from researchers recently. The plasma treatment begins by placing steel fibers into a vacuum chamber, removing the air, and then filling the chamber with selected gas. The oxygen and argon are the commonly used gas for plasma treatment of metals [85]. The steel fibers were treated in the chamber and the designed duration of plasma treatment was between 0 min and 8 min. The results demonstrate that the pullout load and energy of steel fiber improved by 20–40% after oxygen/argon plasma treatment [31,71]. The ability of material to bond with other substances can be measured by its surface energy; such index is also used to evaluate the effectiveness of surface treatment methods [86]. After plasma treatment, the surface energy of steel fibers increased by more than 30%. The variation in surface energy of steel fiber in turn improves the interfacial performance. Compared to the ZnPh conversion coating approach, the plasma treatment is environmentally safe because no toxic solvents are released during the whole process. However, it should be noted that the plasma treatment requires specific equipment and the amount of steel fibers for each treatment remains small-scale.

The addition of nanomaterials into cementitious matrix can modify its microstructure and improve its mechanical strength [87], which is beneficial to the interfacial performance in SFRCC. Compared to the approach of modifying matrix, modifying steel fibers through coating nanomaterials is a more efficient approach. The interfacial transition zone between steel fiber and cementitious matrix is the weakest area in SFRCC. It has been demonstrated that approximately 50% of micropores ranges from 0 to 100 nm and a part of hydration products is characterized by highly porous in interfacial transition zone [61]. Thus, it can be inferred that the interfacial performance of SFRCC can be improved obviously if the interfacial transition zone is targeted reinforcement through nanocoated steel fibers from nanoscale. The nano-SiO_2 can react with $Ca(OH)_2$ to form hydrated calcium silicate (C–S–H) and fill the micropores, enhancing the microstructure of C–S–H and promoting the pore structure of cementitious materials [88]. The application of nano-SiO_2 coating to steel fibers in SFRCC has been explored recently. Sol–gel-derived nanocoating is one of the preferred thin film production methods due to the relative ease of production and the inexpensive equipment utilized [89]. The nano-SiO_2 was prepared and coated on steel fiber surface through sol–gel method. The coating process of nano-SiO_2 is briefly described in Figure 4a, and the role of nano-SiO_2 film at interface is illustrated in Figure 4b. Compared to unmodified steel fiber, the interfacial bonding strength and pullout energy of modified steel fiber improved by 78 and 68%, respectively [49,72]. The reason is that the treated steel fiber can effectively increase the density of microstructure, decrease the porosity, and establish the chemical bonding at the fiber–matrix interface. However, the preparation process of nanocoating film is complicated and the cost of this approach is relatively high, which prevents the commercialization of this approach for interfacial enhancement.

3 Structural performance of SFRCC with interfacial modification

The changes in properties of cementitious matrix and steel fiber contribute to the enhanced interfacial performance, bringing great benefits to the mechanical properties of SFRCC, while it remains a concern on whether such localized interfacial improvement can lead to better global performance of SFRCC structures. The structural performance of SFRCC with interfacial modification has been investigated and analyzed under static and dynamic loads [90,91]. In addition, the workability of SFRCC is another essential factor for field-casting projects. The influence of the enhancement approaches on workability of SFRCC also has been studied.

3.1 Workability

Workability is a key parameter for placement and consolidation of fresh SFRCC [92,93]. Compared to the normal concrete, the water to binder of SFRCC is extreme low (<0.3) and a large amount of fine aggregate is used in

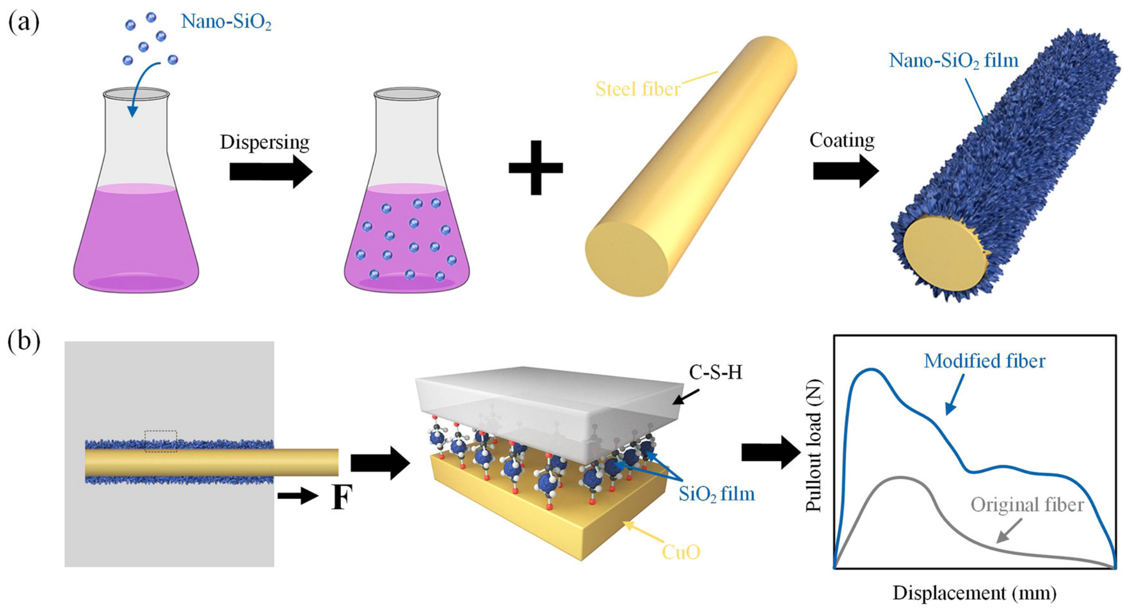

Figure 4: (a) Schematic diagram of the nano-SiO_2 coating process on a steel fiber surface. (b) Pullout behavior of steel fiber with nano-SiO_2 film from SFRCC matrix. The C–S–H binds tightly to CuO through the coated nano-SiO_2 film, resulting in a significant improvement in pullout load.

SFRCC [94,95]. For example, the content of cement and silica fume is more than 800 and 200 kg/m^3, respectively. With incorporation of small steel fibers, the workability of SFRCC is not desirable despite the utilization of high content superplasticizer [96]. The workability of SFRCC is significantly influenced by its water to binder ratio. In the range of 0.14–0.22 (water to binder ratio), the slump flow of SFRCC increased by 40 mm for every 0.2 increase in water to binder ratio [52]. It has been demonstrated that the decrease in water to binder ratio can enhance the interfacial performance of SFRCC, but the reduction in water to binder ratio also brings negative effect on the workability of SFRCC. The content of silica fume and nanomaterials in SFRCC can cause a change in workability of SFRCC [57,61]. The effect of silica fume on the workability of SFRCC is relatively complicated; the relationship between silica fume content and workability is not linear. The optimal content of silica fume was 10–20% for the workability of SFRCC. For the content of nanomaterials, the workability of SFRCC decreases with the rise of nanomaterials content. For example, the slump flow of SFRCC decreased by 65 mm when the 2% nano-SiO_2 was incorporated. Thus, the influence of silica fume and nanomaterials content on workability should be considered when enhancing the interfacial performance of SFRCC.

The basic principle of chemical modification approaches is to coat a film on steel fiber surface, which changes the surface roughness of steel fiber [91]. Such variation can induce a negative effect on the workability of SFRCC. Take the SFRCC containing SCA treated steel fibers for example, when the straight steel fibers were modified by 1 and 3% concentration of SCA, the flowability of fresh cementitious paste reduced by 3 and 6 mm compared to that of reference group, respectively. For the hooked-end steel fibers, the corresponding values decreased by 3 and 7 mm, respectively. However, the obtained flowability values still meet the requirement of field-casting project (>180 mm). Microscale observation shows that the steel fiber surface becomes rough after chemical modification, and the friction between the modified steel fiber and cementitious paste is improved. Therefore, the flowability of SFRCC with chemically modified steel fibers decreases.

3.2 Static load

For the general engineering structures, most of structural members are subjected to static compressive and flexural loads [97,98]. The compression and flexural behavior are the most important mechanical properties of SFRCC. The global mechanical performance of SFRCC with interfacial modification under static load is summarized in Table 2. The reduction in water to binder ratio contributes to the high mechanical strengths of SFRCC. When the water to binder ratio decreased from 0.3 to 0.2, the compressive and flexural strength improved by 29 and 62% at 28 days, respectively [52]. The incorporation of moderate silica fume and nanomaterials brings an enhancement of 9–30% in compressive and flexural strength of SFRCC at 28 days [57,61]. The deformed steel fibers have significant effects on the mechanical strength of SFRCC. Compared to the same content of straight steel fibers, the compressive strength of SFRCC with hooked-end and corrugated fibers increased by 48 and 59% at 28 days, respectively [28,29,62]. The flexural strength of SFRCC with 2 vol% hooked fiber was 34 MPa at 28 days, which improved by 8% compared with that of SFRCC with 2 vol% corrugated fiber [99]. The utilization of chemically modified steel fibers can also enhance the compressive and flexural strengths of SFRCC [91]. The compression test of SFRCC was conducted according to British standard (BS EN) 196–1:2016 at a loading rate of 2.4 kN/s. Three-point bending test was performed to obtain the flexural behavior of SFRCC at a loading rate of 0.2 mm/min. Compared to the reference group, the specimen with SCA modified steel fibers exhibits a 15% enhancement on compressive strength. Similarly, the improvement of 11% on the compressive strength of SFRCC was achieved after utilizing plasma modified steel fibers. The flexural strength of SFRCC was also improved by about 14 and 17% after incorporating SCA and ZnPh modified steel fibers, respectively. It should be noted that the concentration of SCA has an adverse effect on mechanical strengths of SFRCC at early curing age. The deterioration degree of flexural strength reached approximately 5% at 7 days when the steel fibers were modified with 5% concentration of SCA. Such phenomenon is attributed to the fact that SCA can delay the cement setting at early age, and the delay effect disappears with the increase of curing age [100].

The two performance indicators, *i.e.*, cracking behavior and energy absorption capacity, are used to evaluate the tensile properties of SFRCC [101]. The cracking behavior reflects the load bearing capacity after initial cracking under flexural/tensile load, including first crack load, first crack displacement, peak load, and peak load displacement [102]. The schematic diagram of three-point bending test setup for SFRCC is displayed in Figure 5a. The evaluation indexes of cracking behavior can be obtained from load–displacement curves. The energy absorption capacity refers to the resistance to brittle failure under flexural/tensile load, and it can be determined by the area of load–displacement curves [103], as shown in Figure 5a. For the first crack load and peak load displacement, the corresponding values improved by 12 and 33% after incorporating SCA modified steel fibers in SFRCC [91]. Such result shows that chemical modification of steel fiber is effective in promoting the cracking behavior of SFRCC. Meanwhile, the energy absorption capacity of specimen with SCA modified straight steel fibers exhibits the increment of 14% compared to that of specimen with unmodified steel fibers (Figure 5a). For the tensile strength of SFRCC, the corresponding value was increased by 18% after incorporating ZnPh modified steel fibers. Additionally, it is found that the plasma treatment of steel fibers leads to a 19% decrease in total crack area of SFRCC under tensile load [31]. The above results demonstrate that chemical modification of steel fibers is an ideal candidate solution to enhance the compressive, flexural, and tensile performance of SFRCC under static loads.

Table 2: Effect of enhancement approaches on the global mechanical performance of SFRCC

Approaches type	Variables	Global mechanical performance	Refs
Mechanical properties of cementitious matrix	Water to binder ratio	30% in compressive strength and 60% in flexural strength	[52]
Mechanical properties of cementitious matrix	Content of silica fume and nanomaterials	10–30% in compressive and flexural strength	[57,61]
Physical arrangement of steel fiber	Corrugated steel fiber	60% in compressive strength	[29]
Physical arrangement of steel fiber	Hooked steel fiber	50% in compressive strength	[28]
Chemical modification of steel fiber surface	ZnPh coating	20% in flexural and tensile strength	[30,67]
Chemical modification of steel fiber surface	SCA modification	15% in compressive and flexural strength, 50% in peak toughness under dynamic load	[90,91]
Chemical modification of steel fiber surface	Plasma treatment	10% in compressive strength	[31]

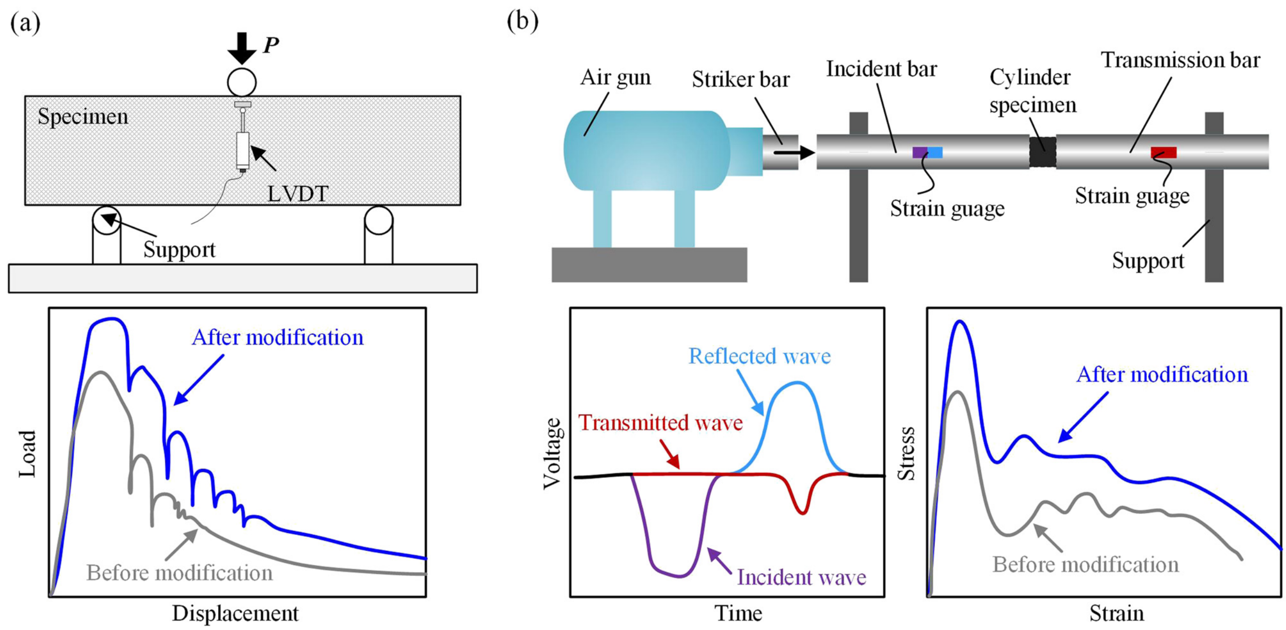

Figure 5: Schematic diagram of static test and dynamic test setup for SFRCC. (a) Three-point bending test. (b) Split Hopkinson pressure bar (SHPB) test. Based on the load–displacement and stress–strain curves, both the static and dynamic performance of SFRCC are enhanced significantly after interfacial modification.

The coupled effect of the interfacial enhancement approaches on static mechanical performance of SFRCC has been investigated [91], and the combination of deformed steel fiber and chemical modification method has a positive effect on the mechanical properties of SFRCC. The compressive and flexural strengths of SFRCC with SCA modified hooked steel fibers increased by 16 and 23%, respectively, relative to those of SFRCC with straight steel fibers. The mechanical performance enhancement originating from the combination of different enhancement approaches is more obvious than that originating from single enhancement approach. To further improve the mechanical performance of SFRCC, the coupled effect of different interfacial enhancement approaches is recommended to be investigated in the future research.

3.3 Dynamic load

Apart from the static loads, the dynamic loads, such as impact or explosive loads, are critical to some key and specialized structures, *e.g.*, nuclear power plants, protective engineering, and high-rise buildings [104,105]. The superior mechanical properties of SFRCC make it a promising candidate material for these structures. However, due to the poor bonding between steel fiber and cementitious matrix, the premature and brittle failure is still observed under the dynamic load with high strain rate [106]. The effect of enhancement approaches on dynamic performance of SFRCC has been investigated and evaluated [90,107]. SHPB test is selected to measure the mechanical properties of SFRCC under the dynamic loading conditions [108], and the schematic diagram of SHPB test setup is presented in Figure 5b. The peak stress, peak toughness, and energy absorption capacity of specimen are calculated and analyzed from stress–strain curves [109], as depicted in Figure 5b. The dynamic performance of SFRCC with interfacial modification is shown in Table 2. At the strain rate of 16–37/s, the peak toughness of specimen containing hooked-end and twisted steel fibers reduced by 14 and 57%, respectively, compared to that of specimen with straight steel fibers. A similar trend was also found for the energy absorption capacity of specimen. It can be inferred that the mechanical properties of SFRCC with deformed fibers are lower than those of SFRCC with straight fibers under dynamic loading conditions. Due to the strong mechanical anchorage between the deformed hooks and cementitious matrix, severe matrix damage was formed shortly before reaching its full interfacial bonding strength [63]. At the strain rate of 160–170/s, the peak toughness had a 52% enhancement by incorporating SCA modified steel fibers in SFRCC compared to that of reference group [90]. The energy absorption capacity of specimen with SCA modified steel fibers also increased more than 20% (Figure 5b), indicating the desirable mechanical performance under dynamic load.

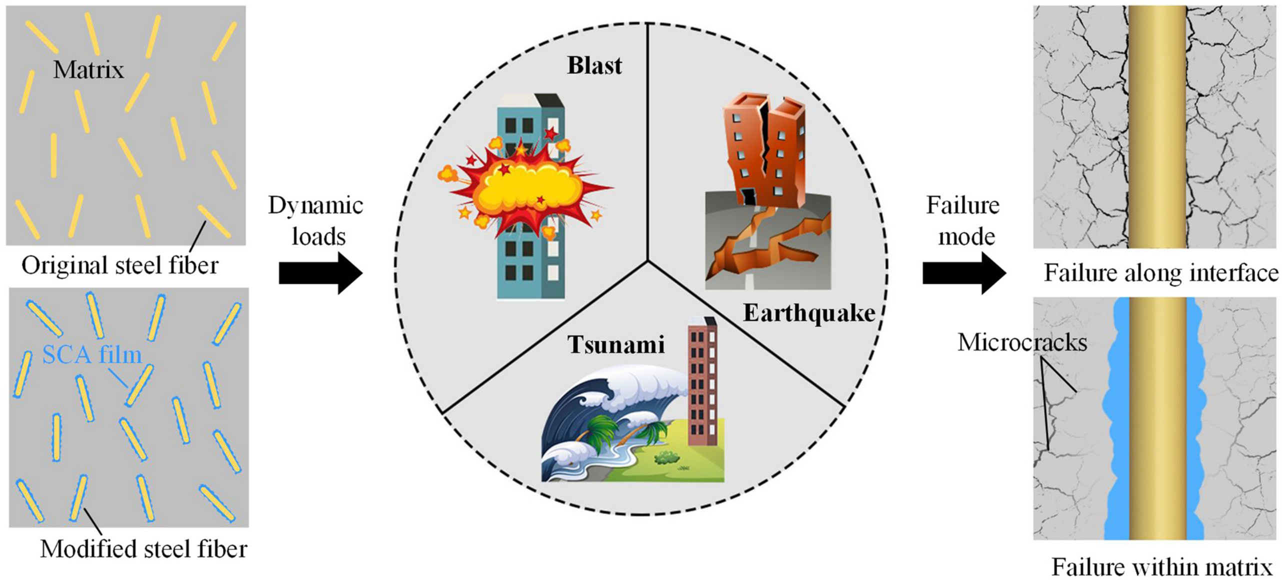

Figure 6: Failure mode of SFRCC with original and SCA modified steel fibers under dynamic loads. For SFRCC with original steel fibers, microcracks appear along the interface due to the weak interfacial performance. For SFRCC with modified steel fibers, microcracks appear within the matrix, contributing to a favorable ductile failure mode.

As for the failure mode, the specimen with SCA modified steel fiber exhibits fewer cracks, smaller debonding zone, and bigger size of fragments. Such failure mode is beneficial to improve the brittle resistance of SFRCC when subjected to the dynamic loads.

3.4 Enhancement mechanisms

The underlying mechanisms of the above enhancement approaches can be summarized as follows. For the approaches about the mechanical enhancement of cementitious matrix and physical arrangement of steel fiber, the variation in mechanical properties of SFRCC originates from the change of physicochemical bond and mechanical bond [26]. The variation of water to binder and the addition of additives improve the microstructure and mechanical strength of cementitious matrix, contributing to the strong physicochemical bond at the interface and high mechanical performance of SFRCC. The utilization of deformed steel fibers significantly improves the anchorage force at interface, leading to the enhancement in interfacial mechanical bond. In this situation, the mechanical performance of SFRCC is improved under static loads.

For the approaches about chemical modification of steel fiber surface, the behind mechanism can be summarized in mechanical, chemical, and physical perspectives. The SCA modification approach is selected to reveal the enhancement mechanism. The morphology and chemical composition of steel fiber surface before and after SCA modification were characterized by atomic force microscopy and Fourier-transform infrared spectroscopy, respectively. SCA modification increases the surface roughness of steel fiber and improves the mechanical friction at the interface [110]. The SCA films are coated on steel fiber surface through the chemical bonding (Cu–O–Si groups) [111]. The strong adhesion between SCA films and cementitious matrix is established by hydrophilicity interaction [91,112]. SCA modification can improve the friction and adhesion at interface. In this situation, the interfacial bond between steel fiber and cementitious matrix enhances significantly. The stress transfer from cementitious matrix to steel fiber becomes more effective [113], which can postpone the crack initiation and propagation. The variation in stress transfer results in higher mechanical strength and better tensile performance of SFRCC under static load. The schematic diagram about the interfacial failure of SFRCC under dynamic load is shown in Figure 6. As the interfacial bond is more tight after SCA modification, most of the microcracks are formed in the cementitious matrix rather than fiber–matrix interface at the initial stage of dynamic load [90]. When the microcracks develop into macrocracks, the modified steel fiber and cementitious matrix still bond together in specimen. However, the macrocracks along the fiber–matrix interface are formed in specimen containing unmodified steel fiber, because the unmodified steel fiber and cementitious matrix are easily bonded. For the SCA modified steel fiber, the fragment includes steel fiber and cementitious matrix can still effectively resist the external loads, leading to a favorable dynamic response and failure mode. Hence, the mechanical performance of SFRCC is significantly improved through SCA modification under dynamic loads.

4 Key challenges and future development

Although the enhancement approaches for interfacial performance between steel fiber and cementitious matrix have been proposed and investigated, the application of these approaches in practical engineering for SFRCC still remains a major challenge, as limited information about the mechanical properties of engineering structures with interfacial modification has been reported. The engineering structures consist of various types of components, and its global performance depends on the mechanical properties of components [114,115]. The existing researches mainly focus on the mechanical properties of SFRCC at the interface and material levels. Meanwhile, the macroscopic damage and deformation of materials always originate from the bonding, fracture, and energy problems at the atomistic scale [116,117]. The interfacial toughening mechanism about SCA modification approach can be revealed through MD simulation [70,118]. Therefore, the bottom-up system ranges from microscale to macroscale, *i.e.*, interface, materials, components, and structures, is the key factor for application of the enhancement approaches in practical engineering. However, such system has not been established at present based on analysis of existing literatures. The effect of interfacial modification on the mechanical properties of components and engineering structures is still unclear, impeding the wide implementation of these enhancement approaches. To address this issue, further researches should be conducted to comprehensively evaluate the global performance of engineering structures with interfacial modification.

As discussed previously, most of the proposed approaches enhance the interfacial performance from microscale or macroscale. The interfacial transition zone between steel fiber and cementitious matrix is the weakest area in SFRCC [119,120]. The mechanical properties of interfacial transition zone are the critical factors in determining the global performance of composite materials [121]. The interfacial transition zone of SFRCC includes micropores and highly porous hydration products [122,123]. It has been demonstrated that the porosity of interfacial transition zone reduces evidently, and the high strength of hydration products increases obviously after incorporating nanomaterials [124,125]. The utilization of nanomaterials is effective in filling the micropores, supplying additional hydrates for cementitious materials, and promoting the quality of hydration products [126]. It can be inferred that the interfacial performance of SFRCC can be enhanced remarkably through the targeted reinforcement for interfacial transition zone from nanoscale. In this case, the best use of nanomaterials for performance improvement can be achieved. More efforts should be made to develop the new enhancement approaches for interfacial performance in SFRCC from nanoscale, *i.e.*, nanomaterials coating technology for steel fiber surface.

Most of construction materials exhibit good performance in a short time, but serious degradation on mechanical properties can be observed over a certain period of time under service conditions [127,128]. Such variation in mechanical performance threats human life and property safety, increases the maintenance cost, and reduces the service life of structures. Apart from mechanical enhancement, the durability of SFRCC is a critical consideration for its application [129,130]. The approaches for interfacial performance enhancement of SFRCC include the incorporation of additives in cementitious matrix, physical arrangement and chemical modification of steel fiber. All the mentioned approaches would change the component and microstructure of SFRCC, which may affect its durability during the service period. Further investigations are suggested to help understand the long-term performance of SFRCC with interfacial modification.

5 Conclusion

As an advanced cementitious material, SFRCC is an ideal candidate material for high-rise structures, long-span bridges, and protective engineering. The flexural and tensile properties of SFRCC are mainly dominated by the interfacial performance between steel fiber and cementitious matrix. In this paper, the technologies for interfacial performance enhancement in SFRCC have been reviewed. The enhancement approaches are classified into three categories, including mechanical enhancement of cementitious matrix, physical arrangement of steel fiber, and chemical modification of steel fiber surface. These approaches can enhance the interfacial performance of SFRCC from the perspectives of mechanical and physicochemical bonds. The underlying mechanisms behind these approaches have been summarized and analyzed. The structural performance of SFRCC with interfacial modification has been evaluated and analyzed under static and dynamic loads. The mechanical improvement of cementitious matrix and physical arrangement of steel fiber contribute to strong friction and anchorage force at interface. The chemical modification approaches can change the surface properties of steel fiber and establish firm bond at interface. The paper can provide an in-depth understanding of technologies for interfacial performance enhancement in SFRCC. Aided with these enhancement approaches, the development and application of SFRCC in innovative structures and megastructures can be accelerated. The durability of materials is closely correlated to the safety and service life of engineering structures, but the long-term performance of SFRCC with interfacial modification still remains unclear. The bottom-up system ranges from microscale to macroscale is a decisive factor for application of these enhancement approaches. However, such system from interface to global performance of engineering structures with interfacial modification has not been established. Further studies are necessary to address the above issues for promoting the application of enhancement approaches in practical engineering. Furthermore, the approach involves that nanoscale reinforcement has emerged as a new development trend to enhance the interfacial performance, and it is envisioned that such new approach will have a profound impact on the development of SFRCC.

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