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A Review of Research on Basalt Fiber Reinforced Polymer Self-Compacting Concrete Columns

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ABSTRACT: As a new type of high-performance concrete, self-compacting concrete (SCC) has been widely used in modern construction projects due to its excellent working performance, construction convenience and good durability. However, compared with common concrete (NC), the elastic modulus of SCC is relatively low, which limits its application in terms of bearing capacity and deformation performance to a certain extent. As a new type of environmentally friendly reinforcement material, basalt fiber reinforced polymer (BFRP) has shown great application potential in the field of concrete structure reinforcement due to its excellent mechanical properties, good corrosion resistance, abundant raw material sources and environmental friendliness. This paper systematically reviews the current research status of BFRP-reinforced SCC columns, focusing on the differences in material properties between SCC and NC, the performance comparison between BFRP and other fiber-reinforced polymer materials, the main reinforcement methods of concrete columns, the experimental research progress of BFRP-reinforced concrete columns, and the current status of numerical simulation research. Through an in-depth analysis of existing research results, the main problems existing in current research are identified, especially the blank areas of BFRP-reinforced SCC columns. Based on these analyses, this paper proposes the key directions for future research, which will provide an important reference for promoting the theoretical research and engineering practice of BFRP-reinforced SCC columns.

1. INTRODUCTION

As one of the most important vertical load-bearing components in the building structure system, the main function of the concrete column is to bear the vertical load from the beam-slab system and transfer these loads safely and effectively to the foundation system (Syal and Goel, 2008). The structural performance of the column directly affects the stability, safety and use function of the entire building. Especially under extreme loads such as earthquakes, the damage of the column is often the key factor leading to the overall collapse of the building (Jin et al., 2018).

With the continuous development of modern construction technology, concrete structures are developing towards large spans, super-high-rises, and complex shapes. This development trend has significantly increased the complexity of structural design and construction (Ali and Moon, 2018; Memon et al., 2020). In the traditional vibrated concrete construction process, especially when the reinforcement is dense, the cross-sectional shape is complex, or the construction space is limited, problems such as insufficient and uneven vibration often occur, resulting in defects such as honeycombs, rough surfaces, and voids inside the concrete (Sahu, 2022).

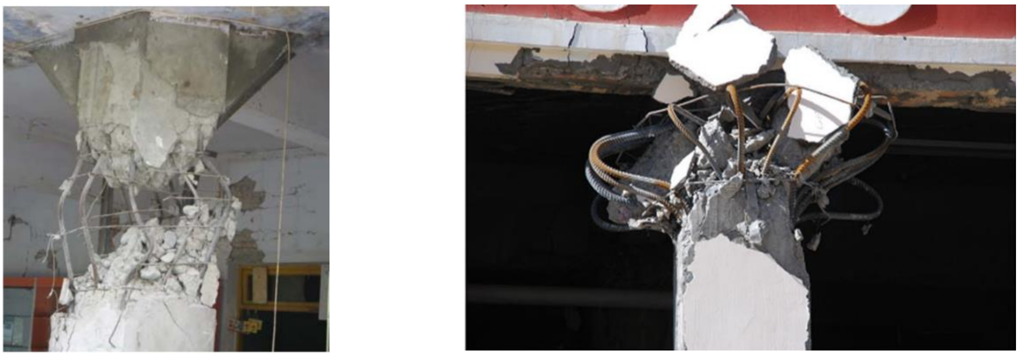
Figure 1: Honeycombing and insufficient vibration problems in columns

In order to solve these problems of traditional vibrated concrete, Japanese scholar Okamura first proposed the concept of self-compacting concrete (SCC) in 1986, aiming to develop a new type of concrete that can flow under its own weight and fully fill the formwork, and can achieve good compaction effect without mechanical vibration even under dense reinforcement conditions (Okamura and Ouchi, 2003). In 1988, Professor Ozawa of the University of Tokyo successfully developed the first batch of SCC prototype materials (Ozawa, 1989).

Compared with traditional vibrated concrete, SCC has many significant advantages. First, SCC has excellent working performance and can flow freely in complex formwork to ensure the uniformity and density of concrete; second, SCC can significantly improve the surface quality of concrete and reduce surface defects; third, the SCC construction process does not require vibration, which greatly reduces labor intensity and construction noise (Mikhaltchouk et al., 2022); in addition, the hardened SCC also exhibits excellent mechanical properties and durability (Domone, 2007; Persson, 2001). These characteristics make SCC have broad application prospects in modern construction projects, especially in high-rise buildings, complex structures and prefabricated component production (Kashani and Ngo, 2020; Siddique, 2019).

However, studies have shown that the elastic modulus of SCC is generally lower than that of ordinary concrete of the same grade, which is mainly due to the lower coarse aggregate content and higher paste content in SCC (Leemann and Hoffmann, 2005; Ahmad et al., 2017). This difference in material properties causes SCC columns to exhibit some characteristics different from NC columns in terms of mechanical performance. In terms of seismic performance, Ghadban et al. (2018) found that although SCC bridge columns have higher ultimate strain, their displacement ductility and energy dissipation capacity are lower than those of NC columns, indicating that SCC columns have certain deficiencies in seismic performance.

The frequent occurrence of earthquake disasters has made structural safety issues increasingly prominent. Historical earthquake damage data show that column damage and failure are one of the main reasons for serious damage to reinforced concrete frame structures and even overall collapse (Zhang et al., 2020). Typical earthquake damage manifestations of columns include concrete cover spalling, longitudinal reinforcement buckling, core concrete crushing, etc. These failure modes seriously threaten the safety of the structure (Su et al., 2015; Wallace et al., 2012).



(a)Wenchuan earthquake of 12th May 2008, China Sichuan (Zhang and Liu, 2008)

(b)Yushu earthquake of 14th April 2010, China Qingha i (Gong et al., 2015)

Figure 2: Typical failure modes of concrete columns under earthquake action

The reinforcement methods of concrete columns mainly include cross-section enlargement method, steel casing reinforcement method and fiber reinforced polymer (FRP) reinforcement method (Raza et al., 2019). Among them, FRP reinforcement technology has become an important technical means in the field of concrete structure reinforcement due to its advantages of high strength, high stiffness, light weight, corrosion resistance and convenient construction (Lam and Teng, 2002).

Among various FRP materials, basalt fiber reinforced polymer (BFRP) has attracted more and more attention in recent years as a new type of environmentally friendly reinforcement material. BFRP is made of natural volcanic basalt, which has abundant reserves and relatively low mining and processing costs (Novitskii and Sudakov, 2004). The production process does not require the addition of toxic additives, is green and environmentally friendly, and does not cause environmental pollution (Sim and Park, 2005). Compared with traditional FRP materials, BFRP not only has good mechanical properties, but also has excellent high temperature resistance, chemical corrosion resistance and aging resistance (Dhand et al., 2015; Zhang et al., 2016).

Although there has been an increasing number of studies on BFRP-strengthened concrete structures in recent years, including columns (Huang et al., 2020; Xie et al., 2023), beams (Duic et al., 2018; He et al., 2023) and slabs (He et al., 2021), research on BFRP-strengthened SCC columns is still very limited. The study by Yu et al. (2014) showed that the behavior of FRP-confined SCC may be different from that of FRP-confined NC of the same strength. Therefore, it is necessary to carry out a systematic study specifically on BFRP-strengthened SCC columns.

2. CHARACTERISTICS AND APPLICATIONS OF SELF-COMPACTING CONCRETE

2.1 Basic Characteristics of SCC

The performance evaluation of SCC is mainly carried out from three key aspects: filling capacity, passing capacity and resistance to segregation (Okamura and Ouchi, 2003). Filling capacity refers to the ability of fresh concrete to flow into all spaces in the formwork under its own weight without bleeding and segregation (Sonebi et al., 2007). Passing capacity refers to the ability of fresh concrete to pass through the narrow space between dense steel bars under its own weight without clogging and segregation (De Schutter et al., 2008). Resistance to segregation refers to the ability of fresh concrete to resist the separation of paste and aggregate (Wani and Ganesh, 2022).

In order to accurately evaluate these key properties of SCC, the European Project Group (The European Project Group, 2005) and the Chinese standard (JTJ/T 283, 2012) have developed corresponding test methods and performance classification standards. The European standard recommends the use of five standard test methods, including slump expansion test, V-funnel test, J-ring test, L-box test and sieve separation test, while the Chinese standard recommends the use of four test methods, including slump expansion test, T500 test, J-ring test and sieve separation test.

Table 1 : Performance levels specified by European standards

Property	Parameter	Classification stipulated in (The European Project Group, 2005)	
		Class	Range
Filling Ability	Slump flow	SF1	550-650
		SF2	660-750
		SF3	760-850
	V-Funnel time	VF1	≤8.0s
		VF2	9.0-25.0
Passing Ability	J-ring blocking step	PJ1	≤10 with 12 rebars
		PJ2	≤10 with 16 rebars
	Passing ability ratio in L-box	PL1	≥0.8 with 2 rebars
		PL2	≥0.8 with 3 rebars
Segregation Resistance	Segregation portion	SR1	≤20%
		SR2	≤15%

Table 2: Performance levels specified by Chinese standards

Property	Parameter	Classification stipulated in the Chinese Standard (JTJ/T 283 , 2012)	
		Class	Range
Filling Ability	Slump flow	SF1	550-655
		SF2	660-750
		SF3	760-850
	T500(s)	VS1	≥2.0s
		VS2	<2.0s
Passing Ability	The difference value between slump flow and J-ring flow	PA1	25<PA1≤50
		PA2	0≤PA2≤25
Segregation Resistance	Segregation portion	SR1	≤20%
		SR2	≤15%

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In practical applications, the performance grade of SCC needs to be determined according to specific engineering conditions. For example, SF1 grade SCC is suitable for unreinforced or under-reinforced components; SF2 grade is suitable for most conventional structural components such as columns and walls; SF3 grade is suitable for vertical structural components with dense reinforcement and complex shapes (The European Project Group, 2005; JTJ/T 283, 2012).

2.2 SCC mix design

The mix design of SCC is a key step in obtaining high-quality SCC. Since SCC needs to avoid segregation and bleeding while ensuring high fluidity, its mix design is more complicated than that of ordinary concrete, and special attention must be paid to the selection and proportion control of each component material. The constituent materials of SCC are similar to those of ordinary concrete, including cement, water, coarse and fine aggregates, and admixtures, but there are significant differences in the proportions of each component, especially higher powder content, lower water-cement ratio, and less coarse aggregate content (Shi et al., 2015).

At present, scholars at home and abroad have proposed a variety of SCC mix design methods, mainly including empirical design method, fixed stone volume method, compressive strength method, dense aggregate stacking method and statistical factor model method (Ashish and Verma, 2019; Shi et al., 2015; JTJ/T 283, 2012). Each method has its theoretical basis and applicable conditions. In practical application, it is necessary to select the appropriate method according to the specific situation.

The empirical design method is the earliest proposed SCC mix design method, which was proposed by Okamura and Ozawa in 1995 (Okamura and Ozawa, 1995). The basic principles of this method include: (1) the coarse aggregate content is fixed at 50% of the solid volume; (2) the fine aggregate content is fixed at 40% of the mortar volume; (3) the water-powder ratio (volume ratio) is selected between 0.9 and 1.0 according to the properties of the powder; (4) the self-compacting property is ensured by adjusting the amount of high-efficiency water reducer and the final water-powder ratio (Okamura, 1997). This method is simple to operate and easy to master, but it requires multiple trial mixes to determine the optimal mix ratio. In addition, in order to obtain higher workability and moderate viscosity, it may be necessary to add more high-efficiency water reducer, which not only increases the cost but also may cause delayed setting of concrete.

The fixed stone volume method is developed on the basis of the empirical design method. This method takes the content of coarse aggregate in concrete and the content of fine aggregate in mortar as the key parameters affecting SCC performance. The specific suggestions are: (1) fix the volume of coarse aggregate between 0.28-0.35m^3/m^3 concrete; (2) fix the content of fine aggregate in mortar to 42%-45%; (3) calculate the amount of water and the amount of each cementitious material according to the water-cement ratio of concrete and the proportion of admixtures (JTJ/T 283, 2012). This method is currently the SCC preparation method recommended by Chinese technical regulations and has good practicality.

The compressive strength method is based on the ACI 211.1 standard and the EFNARC guidelines, and determines the content of cement, mineral admixtures, water and aggregates by the required compressive strength (Kheder and Al Jadiri, 2010). This method can reduce the number of trial mixes, but it requires comprehensive consideration of all components of the SCC mixture for proportion adjustment. The dense aggregate packing method determines the mixture proportion by obtaining a packing model with the minimum voids between aggregates, and then fills the voids between aggregates with paste (Ashish and Verma, 2019). This method is simple in principle and requires less cementitious material, but there is no clear explanation on how to determine the optimal sand ratio or packing factor, and these values usually need to be assumed empirically.

The statistical factor model method was developed by Khayat et al. (1999) to perform mix design by establishing statistical relationships between mixture parameters and concrete properties. This method analyzes the effects of different key parameters (such as cement and mineral admixture content, water-cement ratio, coarse aggregate volume, etc.) on the workability and compressive strength of fresh and hardened SCC (Shi et al., 2015). Although this method can also minimize the number of trial mixes, it still requires intensive laboratory testing for new materials.

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Table 3: Typical ranges of concrete mix proportions

Constituent	The Chinese guidelines for SCC		The European guidelines for SCC	
	Typical range by mass (kg/m 3)	Typical range by volume(liters/m 3)	Typical range by mass (kg/m 3)	Typical range by volume(liters/m3)
Powder	400-550	N/A	380-600	N/A
Paste	N/A	N/A	N/A	300-380
Water	≤190	≤190	150-210	150-210
Fine aggregate	N/A	42-45% by volume of the mortar	Content balance the volume of the other constituents	
Coarse aggregate	N/A	SF1: 32-35%; SF2: 30-33%; SF3: 28-30% By volume of the mix	750-1000	270-360
Water-powder ratio	N/A	N/A	N/A	0.85-1.10
Water-binder ratio	≤0.45	N/A	N/A	N/A

2.3 Main differences between SCC and NC

Although the constituent materials of SCC and NC are basically the same, there are significant differences between them in terms of material composition, mechanical properties and structural properties due to differences in mix design concepts and performance requirements. A deep understanding of these differences is of great significance for the rational application of SCC and the development of appropriate reinforcement technologies.

Differences in material composition

The constituent materials of NC and SCC are essentially the same, including cement, water, coarse aggregate, fine aggregate, mineral admixtures and chemical admixtures. However, in order to achieve the high fluidity and self-compacting properties required for SCC, the proportions of the components are significantly different from those of NC. Figure 2.1 intuitively shows the differences in material composition between NC and SCC (Dey et al., 2021).

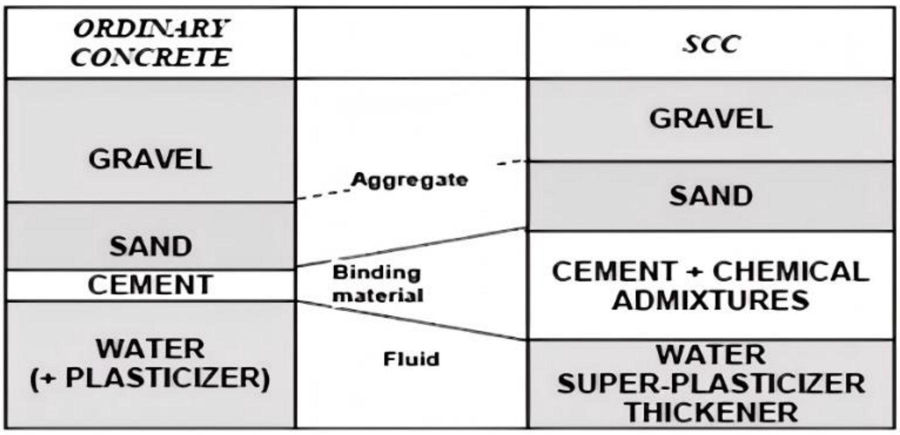

Figure 3: in the original text - Composition comparison of NC and SCC

As can be seen from Figure 3, compared with NC, the typical characteristics of SCC include: (1) higher powder content, usually requiring the use of more cement and mineral admixtures; (2) reduced volume of coarse aggregate, which helps to improve the fluidity of concrete; (3) lower water-cement ratio to ensure the strength and durability of concrete; (4) high-efficiency water reducer and/or viscosity regulator must be used, which is not necessarily required in NC design (Geiker and Jacobsen, 2019; Okamura and Ouchi, 2003). These composition differences enable SCC to avoid segregation while maintaining good fluidity and achieve self-compacting effect, which is particularly suitable for structural members with dense reinforcement (Siddique, 2019).

The difference in material composition not only affects the performance of fresh concrete, but also has an important impact on the mechanical properties and long-term performance of hardened concrete. For example, higher paste content and lower coarse aggregate content will lead to lower elastic modulus and increased shrinkage of SCC, which need to be considered in structural design and application.

Differences in mechanical properties

The difference in material composition directly affects the mechanical properties of SCC and NC. Several studies have compared the mechanical properties of SCC and NC at the same strength level and found significant differences between the two. Leemann and Hoffmann (2005) showed that despite having similar compressive strength, SCC tends to exhibit lower elastic modulus, higher shrinkage and higher creep rate. They found that the properties mainly controlled by the water-binder ratio (such as compressive strength, flexural strength, and oxygen permeability) were comparable between SCC and NC, but the properties related to aggregate content and paste characteristics were significantly different.

Ahmad et al. (2017) systematically compared the hardening properties of NC and SCC. The results show that when the water-cement ratio is 0.35, the compressive strength and splitting tensile strength of SCC are slightly higher than those of NC, which may be due to the better compactness and interface transition zone performance of SCC. However, the failure modulus and elastic modulus of SCC are lower than those of NC, which is mainly attributed to the lower coarse aggregate content in SCC. Coarse aggregate plays a skeleton role in concrete, and a reduction in its content will inevitably lead to a decrease in overall stiffness.

Based on the results of multiple studies, it can be found that the elastic modulus of SCC is usually 5%-15% lower than that of NC with the same strength. This difference is mainly caused by the smaller volume of coarse aggregate in SCC mixtures. At the same time, for the same compressive strength, the tensile strength of SCC is often slightly higher than that of NC, which may be related to the more uniform microstructure and better interfacial bonding of SCC (Leemann and Hoffmann, 2005; Ahmad et al., 2017). These differences in mechanical properties will affect the stress behavior and deformation characteristics of structural components, and must be fully considered when designing structures and formulating reinforcement plans.

Differences in column structure performance

The differences between SCC and NC at the material level will inevitably be reflected in the performance of structural components. Many scholars have conducted comparative studies on the structural performance of reinforced SCC columns and NC columns, revealing the differences between the two in terms of bearing capacity, deformation performance and failure mode.

Earlier studies by Galano and Vignoli (2008) and Paultre et al. (2005) showed that the overall behavior of reinforced SCC columns under concentric and eccentric uniaxial compressive loads is basically similar to that of reinforced NC columns. However, a detailed comparative analysis found that the SCC columns exhibited slightly lower bearing capacity, higher ductility and a higher number of cracks. These differences were mainly attributed to the lower elastic modulus of SCC. The lower elastic modulus means that SCC will produce greater strains at the same stress level, which explains why SCC columns show higher ductility. At the same time, due to the lower stiffness, SCC columns will produce more microcracks before reaching the ultimate bearing capacity, and the development and expansion of these microcracks will eventually lead to the failure of the component.

In terms of seismic performance, Ghadban et al. (2018) conducted a systematic comparative study on reinforced SCC bridge columns and NC bridge columns. The results show that for the same concrete strength, SCC has a higher ultimate strain and a lower elastic modulus. This difference in material properties leads to significantly different structural performance: the reinforced SCC bridge columns exhibit lower displacement ductility and higher drift ratio. Under cyclic lateral loading, the energy absorbed by the SCC columns before failure is lower than that of the NC columns, which indicates that the seismic performance of the SCC columns is relatively weak. This finding is of great significance for structural design in earthquake zones, and appropriate measures need to be taken in the design to compensate for the shortcomings of SCC columns in terms of seismic performance.

Based on the above research findings, the main differences in the structural performance between SCC columns and NC columns can be summarized as follows: (1) Due to the lower elastic modulus, the initial stiffness of SCC columns is smaller and they will produce larger deformations under the same load; (2) The ultimate bearing capacity of SCC columns is slightly lower than that of NC columns, but the difference is usually in the range of 5%-10%; (3) SCC columns exhibit higher ductility, which may be advantageous in some cases; (4) SCC columns have more cracks but smaller cracks, and the crack distribution is more uniform; (5) Under the action of earthquakes, the energy dissipation capacity of SCC columns is weaker, and special attention should be paid to their seismic design.

These differences in structural performance indicate that the design and reinforcement methods of NC columns cannot be simply applied directly to SCC columns, and research specifically targeting SCC columns is needed, especially in terms of reinforcement technology. Considering the widespread application of SCC in modern buildings and its shortcomings in some performance aspects, it is of great theoretical and practical significance to study suitable reinforcement methods to improve the bearing capacity and seismic performance of SCC columns.

3. CONCRETE COLUMN REINFORCEMENT METHOD

3.1 Cross-section enlargement method

The cross-section enlargement method, also known as the cross-section enlargement method or the external concrete method, is a traditional method for strengthening concrete structures. This method increases the cross-sectional area of the column by pouring a new concrete layer on the surface of the original concrete column, and at the same time configures an appropriate amount of longitudinal steel bars and stirrups, thereby improving the bearing capacity, stiffness and stability of the column (Khalid Heiza et al., 2014). Figure 3.1 shows the basic structural form of the cross-section enlargement method.

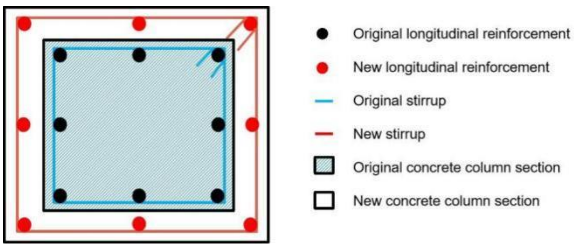

Figure 4: Section enlargement method

The reinforcement mechanism of the cross-section enlargement method is mainly reflected in the following aspects: (1) the compressive bearing capacity of the component is directly improved by increasing the cross-sectional area; (2) the newly added longitudinal steel bars and stirrups enhance the stress performance and ductility of the component; (3) the new and old concrete work together to form a composite section, which improves the overall stiffness; (4) the outer concrete forms a constraint on the original component, improving its stress performance. This method is widely used in engineering practice, the technology is mature and the reinforcement effect is reliable.

However, this method requires a long construction period, the increase in cross-sectional size will reduce the usable space, and the added concrete and steel bars will significantly increase the deadweight of the structure, which may change the natural frequency of the structure (Habib et al., 2020). From the perspective of environmental impact, the construction process will generate noise and dust pollution, and the increased resource consumption and energy demand may lead to higher carbon dioxide emissions (Puskas and Moga, 2015).

3.2 Steel casing reinforcement method

Steel casing reinforcement, also known as external steel reinforcement, is a reinforcement method that uses structural adhesive or welding to bond or weld steel plates, steel sections and other steel components to the surface of concrete columns, thereby improving the bearing capacity and deformation performance of the column (Raza et al., 2019). Figure 3.2 shows the typical structural form of the steel casing reinforcement method.

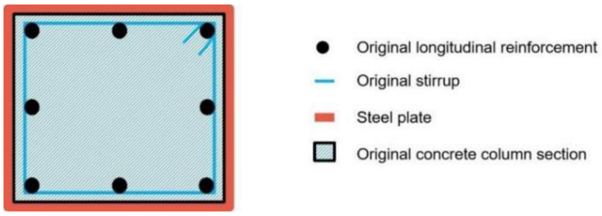

Figure 5: Steel casing reinforcement method

The working principle of the steel casing reinforcement method is based on the following aspects: (1) The steel casing directly participates in the load bearing, shares part of the axial load, and improves the overall bearing capacity; (2) The steel casing provides lateral constraints to the core concrete, so that the concrete is in a three-dimensional compressive state, thereby improving its compressive strength and ductility; (3) The steel casing limits the lateral deformation of the concrete, delays the development of cracks, and improves the failure mode of the component; (4) The high strength and good plasticity of steel improve the overall ductility of the component.

Steel casing reinforcement method has many advantages, which makes it widely used in engineering practice. This method is relatively simple and fast to construct. The main processes include surface treatment, steel plate installation and grouting, and the construction period is short. After reinforcement, the cross-sectional dimensions of the components increase only slightly, which basically does not affect the building's usable space and appearance. The high strength of steel makes it possible to achieve significant reinforcement effects with thinner steel plates, with limited increase in the deadweight of the original structure and no significant change in the dynamic characteristics of the structure (Islam and Hoque, 2015). In addition, the steel casing reinforcement method is applicable to components under various stress states, including bending, shear, compression and tension, and has a wide range of applicability (Raza et al., 2019).

In actual engineering applications, the success of the steel casing reinforcement method depends largely on the construction quality, especially the bonding quality between the steel plate and concrete and the connection quality between the steel plates. Therefore, when choosing this method, you need to ensure that you have an experienced construction team and strict quality control measures.

3.3 FRP reinforcement method

Fiber reinforced polymer (FRP) reinforcement is a reinforcement method that pastes high-performance fiber composite materials on the surface of concrete components to improve the bearing capacity and deformation performance of components through the high strength and high elastic modulus of FRP materials (Lam and Teng, 2002). Since FRP reinforcement technology was applied to civil engineering in the 1980s, it has become one of the important methods for strengthening concrete structures due to its unique advantages. Figure 3.3 shows the basic form of FRP reinforced concrete columns.

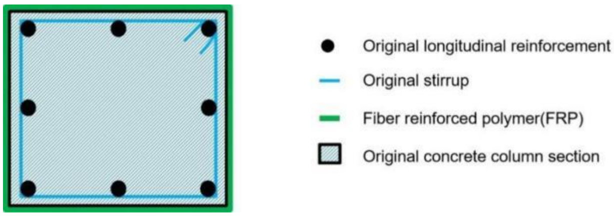

Figure 6: FRP reinforcement method

The mechanism of action of FRP reinforced concrete columns mainly includes: (1) The circumferentially wrapped FRP provides effective lateral constraints on concrete, placing the concrete in a three-dimensional compressive state, significantly improving its compressive strength and ductility; (2) The high tensile strength of FRP materials can effectively limit the lateral expansion of concrete and delay the development and growth of longitudinal cracks; (3) The good bonding performance between FRP and the concrete surface ensures that the two work together to form a composite force system; (4) The wrapping effect of FRP can prevent the concrete protective layer from peeling off, protect the internal steel bars, and improve the integrity of the component.

FRP reinforcement method has many significant advantages, which makes it occupy an important position in the field of modern structural reinforcement. First, FRP materials have extremely high tensile strength (up to 3000 MPa or more) and good corrosion resistance, and can maintain stable performance in harsh environments (Hollaway, 2010). Secondly, FRP material is light in weight and its density is only 1/5-1/4 of that of steel. After reinforcement, it hardly increases the deadweight of the structure and will not change the stress state of the original structure. Third, FRP reinforcement construction is convenient, mainly including surface treatment, primer coating, FRP pasting and surface protection. It does not require large-scale mechanical equipment, has a short construction period, and has little interference with normal use (Amran et al., 2018). Fourth, FRP reinforcement does not change the cross-sectional dimensions of the components, does not occupy the usable space, and does not affect the functionality and aesthetics of the building (Cao, 2020). Fifth, a large number of studies and engineering practices have proved that FRP reinforcement can significantly improve the ultimate compressive strength of concrete (the increase can be up to 50%-200%) and ductility (the increase can be up to 200%-800%), and the reinforcement effect is remarkable (Lam and Teng, 2002; Tarawneh and Majdalaweyh, 2020).

Compared with other reinforcement methods, FRP reinforcement is particularly outstanding in improving ductility. Studies have shown that the stress-strain curve of FRP-confined concrete presents a bilinear characteristic. The existence of the second rising section allows the component to continue to bear loads and produce large deformations after reaching the peak stress. This improvement in ductility is of great significance for improving seismic performance (Ghernouti et al., 2012). In addition, the anisotropic characteristics of FRP materials allow for directional reinforcement according to force requirements, which improves the pertinence and efficiency of reinforcement. From the perspective of sustainable development, FRP reinforcement requires less material, the construction process is clean and environmentally friendly, and no construction waste is generated. Due to its excellent durability, it reduces the need for later maintenance and replacement, and reduces the environmental impact of the entire life cycle (Sbahieh et al., 2022).

4. BFRP MATERIAL CHARACTERISTICS AND APPLICATIONS

4.1 Basic Characteristics of BFRP

Basalt fiber reinforced polymer (BFRP) is a high-performance composite material made from natural volcanic basalt, which is made by high-temperature melting, drawing, infiltration and other processes and then compounded with a resin matrix. Basalt is one of the most abundant volcanic rocks on Earth, with huge global reserves and relatively low mining costs, which gives BFRP a significant resource advantage (Novitskii and Sudakov, 2004).

The production process of basalt fiber is relatively simple and environmentally friendly. After the basalt rock is crushed, it is melted at a high temperature of 1450-1500℃ and drawn into continuous fibers through a platinum-rhodium alloy drawing plate. The fiber diameter is usually 9-23μm. The entire production process does not require the addition of any chemical additives, does not produce toxic or hazardous substances, and waste can be recycled, making it a truly green and environmentally friendly material (Sim and Park, 2005). In contrast, the production of carbon fiber requires complex chemical treatment and high-temperature carbonization process, which consumes a lot of energy and may cause environmental pollution. Although the production process of glass fiber is relatively simple, a variety of chemical components need to be added to the raw materials.

In order to ensure that the fibers can bear the force synergistically and give full play to their excellent performance, it is crucial to select a suitable resin matrix. The commonly used resin matrices in BFRP mainly include epoxy resin and vinyl ester resin (Fiore and Valenza, 2013; Wang et al., 2016). Epoxy resin has excellent mechanical properties, good bonding properties and chemical corrosion resistance, and is currently the most widely used resin matrix. Vinyl ester resin has better corrosion resistance and fatigue resistance, and is particularly suitable for highly corrosive occasions such as marine environments. By optimizing the ratio of fiber to resin and interface treatment technology, BFRP composites with excellent performance can be obtained (Yao et al., 2016).

BFRP exhibits a series of excellent performance characteristics: tensile strength can reach 1000-2300MPa, elastic modulus is 45-91GPa, elongation is 1.6%-3.0% (Sim and Park, 2005); excellent chemical corrosion resistance and aging resistance; excellent high temperature resistance, with an operating temperature of up to 650℃ (Zhang et al., 2016).

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4.2 Comparison of BFRP and other FRP materials

Deak and Czigany (2009) found that the average tensile strength of basalt fiber is significantly higher than that of E glass fiber. Chairman and Babu (2013) showed that the tensile strength of BFRP is 23% higher than that of GFRP. Wu et al. (2010) showed that the average tensile strength and elastic modulus of BFRP are about 10% and 5% higher than those of GFRP, respectively. Yao et al. (2016) made a comprehensive comparison of different FRPs and found that the performance indicators of BFRP are at an intermediate level.

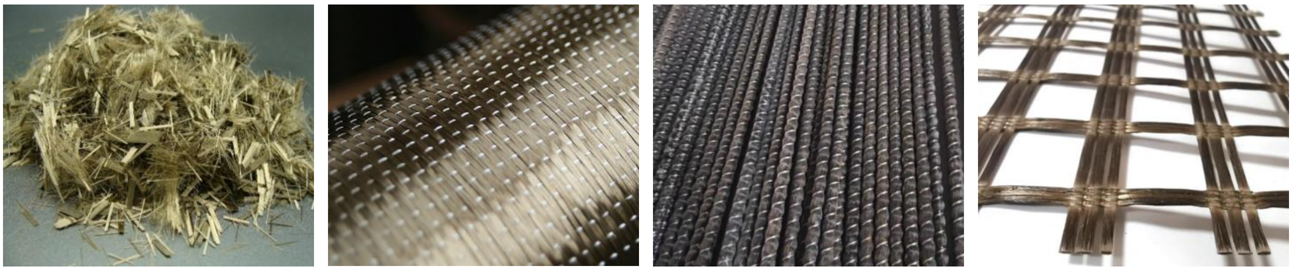
Table 3: Main mechanical properties of different FRPs

Type of FRP	Tensile Strength (MPa)	Elastic Modulus (GPa)	Ultimate Strain (%)
CFRP	610-4340	70-580	0.5-1.82
GFRP	480-1600	30-87	1.2-3.1
AFRP	200-2540	41-125	1.8-4.4
BFRP	1035-2332	45-91	1.6-3.0

A comprehensive comparison shows that CFRP has the best performance but is expensive (Campione et al., 2015); GFRP has a lower cost but relatively weaker corrosion resistance (Deak and Czigany, 2009; Shettar et al., 2018); AFRP has good impact resistance but obvious creep (Yao et al., 2016); BFRP has a good overall cost-effectiveness.

4.3 Application of BFRP in civil engineering

BFRP is used in various forms in civil engineering, including chopped basalt fibers, BFRP sheets, BFRP tendons and BFRP meshes.



(a) Chopped Basalt fibers (b) BFRP sheets (c)BFRP bars (d) BFRP grids

Figure 7: Application forms of basalt fiber

Chopped basalt fibers are mainly used for the reinforcement and modification of concrete (John and Dharmar, 2021). BFRP sheets are currently the most widely used form in the field of structural reinforcement (Madotto et al., 2021; Wei et al., 2018). BFRP bars are mainly used as stress reinforcement or prestressed bars in concrete structures (Wu et al., 2023). BFRP grids are often used in conjunction with engineering cement-based composites (D'Anna et al., 2018).

5. RESEARCH PROGRESS OF BFRP REINFORCED CONCRETE COLUMNS

5.1 Experimental study

Table 4: Summary of studies on BFRP strengthened concrete columns

Author and Year	Paramet-ers	Conc-rete types	Sh-ape	Size	Type of wrapping	FRP layers	Steel bars	Num-ber of spec-imens	Findings	Future recommendation
Deng et al., 2012	FRP layers, creoss-section shape	NC	C and S	150 × 300 100 × 00 × 300	full wrapping	B2, B3, B4	N/A	24	The compressive strength increases with the number of BFRP layers, and cylindrical specimens were better strengthened than quadrate specimens. BFRP significantly improved the bearing capacity and ductility of specimens. The strength model agree well with the test values.	More data are needed to validate the model
Liu et al., 2015	FRP layers, cross aspect ratio(h/b)	NC	S and R	150	full wrapping	B1, B2	N/A	45	BFRP wrapping is more effective in square sections than in rectangular sections, and the strength and strain increases with the number of BFRP layers increase.	Only considered FRP layers and cross aspect ratio(h/b), more parameters need to be consider.

				× 150 × 300 The aspect ratio h/b was 1.0, 1.25, 1.5, 1.75, and 2.0					As the aspect ratio increases, the confined effect decreases until it becomes insignificant at an aspect ratio of greater than 1.75.	
Campione et al., 2015	FRP layers, type of wrapping	NC	C	150 × 300	full and Partial wrapping	B1, B3	N/A	26	The confinement effectiveness of BFRP wraps is related to the reinforcement ratio and, thus, to the thickness of the strips and the number of layers. BFRP can stabilize the post-peak behavior of concrete and increase its strength and ductility.	More research is required to examine the accuracy of the models also with reference to specimens with varying geometric and material properties.

Li et al., 2017	Fiber wrapping approach, type of FRPs	NC	C	150 × 300	full wrapping	B2, C2, G2, B1+C1, B1+G1,C1+G1,B1+C1+G1	N/A	30	The bearing capacity and ductility of concrete columns were efficiently improved through hybrid FRP confinement. A strength model and a stress-strain relationship model of hybrid FRP confined concrete columns were proposed.	Much more test data are required for the improvement/validation of the proposed model.
Wei et al., 2018	FRP layers, type of FRP, steel spiral's spacing	NC	C	150 × 300	full wrapping	B1, B2, C1, C2	Hoop bars: Ø 6 the spacing of the steel spirals(20,40,60)	53	Increasing the number of FRP layers resulted in increased post-peak stiffness and residual strength, as well as decreased stress degradation rate after FRP fracture, when the spacing of steel spirals decreased. A new model was proposed to evaluate the axial strength of FRP-steel-confined concrete columns, taking into account the contributions of both steel spirals and FRP.	More data should be investigate to validate the model
Suon et al., 2019	Cross-section	NC	C and	150	full wrapping	B3, B6, B9	N/A	56	The effectiveness of BFRP confinement	It needs further experimental

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	shapes, corner radius, FRP layers		S and R	× 300 150 × 50 × 300 106 × 12 × 300					in square and rectangular specimens was increased with an increase in corner radius. The low precision in predicting the ultimate axial strain of BFRP-confined concrete specimens across all seven models may be due to unaccounted corner radius effects and varying strain efficiency factors in the study.	verification on how corner radius affect the ultimate strength and strains
Huang et al., 2020	Cross-section shapes, FRP types, FRP layers	NC	C and S	112.8 × 515 100 × 00 × 515	full wrapping	B1, B2, B1+C1	N/A	30	BFRP confinement remarkably improved the compressive strength and ultimate strain of concrete with increasing layers, especially in the circular columns.	more experiments should be carried out to enlarge the database for FRP-wrapped concrete, and more parameters need to be investigated
Xie et al., 2023	corner radius,	NC	S	150	full wrapping	B2, B4	Longitudinal bars 4	14	The externally bonded BFRP can improve the strength	The experimental data in this paper is limited, more BFRP-confined

	FRP layers			× 150 × 450			Ø 10 Hoop bars: Ø 4@85		and ductility of the square RC columns, especially with more BFRP layers and a larger corner radius. The proposed equation can well predict the strain efficiency factor of BFRP-confined square RC columns.	specimens of the same type require further investigation.
Sivasankar et al., 2024	FRP layers	NC	C	150 × 300	full wrapping	B1, B2, B3	Longitudinal bars 6Ø8 Hoop bars: Ø6@135	12	The BFRP sheets greatly increased the compressive strength and strain related to bare RC samples. All the BFRP wrapped samples displayed fiber rupture after reaches the maximum compressive force. This ensures the perfect bonding of BFRP sheets with RC sample. Overall results suggested that the three layers wrapped specimen performed comparatively better than that of one and two layers.	Only considered FRP layers, and more parameters need to be investigated

Ahmad et al., 2021	FRP types, FRP layers	Geopolymer Concrete	C	153 × 306	full wrapping	B2, B4, B6, G2, G4, G6	N/A	21	The confinement of BFRP is more effective than the GFRP due to the higher elastic modulus and larger rupture strain of the former. Fiber-reinforced polymer-confined geopolymer concrete stress-strain behavior is different than the FRP-confined Ordinary Portland Concrete.	Further research needs to be conducted on the development of a confinement model for FRP-confined geopolymer concrete.
Li et al., 2023	FRP layers, bamboo strips content	Ceramsite concrete	C	150 × 300	full wrapping	B1, B2, B3	N/A	18	With the increase of BFRP layers, the bearing capacity and deformation capacity of the specimen increase. A stress–strain model suitable for BFCCCs reinforced with BSs was proposed, and the calculation results were in good agreement with the test results.	More data are needed to validate the model
Li et al., 2024	FRP types, FRP layers	Lightweight aggregate concrete	S	100	full wrapping	B2, C2, B4, C4	N/A	15	Compared with circular columns, the improvement in strength and ductility was reduced to a certain extent due to the square shape of the cross sections	The research only considers the type and thickness of FRP, and does not take into account corner radius, concrete strength, and eccentric compression.

									and stress concentrations at corners.	
				× 100					CFRP demonstrated a more pronounced effect on enhancing the bearing capacity of the specimens, and BFRP had a more notable effect on increasing the ultimate strain of the specimens.	These aspects still need further in-depth research to form a complete research system.
				× 300					Due to the brittleness and low expansion of lightweight aggregate concrete, the stress-strain curve showed weak confinement behavior, and there was a significant decline after the peak point.	

The study by Deng et al. (2012) showed that BFRP reinforcement can significantly improve the compressive strength and peak strain of concrete columns, and the reinforcement effect of circular cross-section is better than that of square cross-section. (2015) found that BFRP wrapping in square sections is more effective than in rectangular sections, and the confinement effect decreases as the aspect ratio increases. Campione et al. (2015) studied the reinforcement effect of BFRP under monotonic and cyclic axial loads and found that the effectiveness of BFRP confinement is related to the reinforcement ratio and the number of layers.

Li et al. (2017) studied the effect of hybrid FRP confinement and found that it can effectively improve the bearing capacity and ductility of concrete columns. Wei et al. (2018) studied FRP-steel confined concrete columns and proposed a strength model considering the contribution of steel bars and FRP. Huang et al. (2020) found that the enhancement ratio of compressive strength and ultimate strain increased with the number of FRP layers.

Xie et al. (2023) and Sivasankar et al. (2024) studied BFRP strengthened reinforced concrete columns. Ahmad et al. (2021) studied BFRP-confined geopolymer concrete. Li et al. (2023) studied BFRP-confined ceramsite concrete. Li et al. (2024) studied BFRP and CFRP strengthened lightweight aggregate concrete columns.

However, most studies focus on ordinary concrete columns, and research on BFRP-reinforced SCC columns is still lacking. In addition, most tests use monotonic axial loads, and the performance under cyclic loading is insufficient.

5.2 Numerical simulation study

Huang et al. (2020) established a three-dimensional numerical model of FRP-confined concrete columns using ABAQUS software. The simulation results were in good agreement with the experimental results, but there were some differences in the late plastic stage.

Other numerical studies on FRP-reinforced concrete columns include: Hajsadeghi et al. (2011) used ANSYS to analyze square/rectangular RC columns; Mazzucco et al. (2016) used ABAQUS to study CFRP-reinforced concrete columns; Jin et al. (2020) studied the size effect of GFRP-confined concrete columns; Ali et al. (2021) used the CDP model to analyze FRP-confined short square RC columns.

5.3 Research gaps

Through a systematic analysis of the existing literature, it is found that there is a significant gap in the research field of BFRP strengthening of SCC columns. First, in terms of mix design, although Europe and China have developed their own SCC standard systems, how to develop a mix design method that can meet the requirements of both standards still needs in-depth exploration. This cross-standard mix design is of great significance for promoting international engineering cooperation and technical exchanges. However, research in this area is still in its infancy.

More importantly, existing research on BFRP reinforcement mainly focuses on ordinary concrete columns, while special research on SCC columns is extremely limited. Considering the essential differences between SCC and NC in terms of material composition, mechanical properties and structural behavior, simply transplanting the research results of BFRP reinforcement of NC columns to SCC columns may lead to design deviations and safety hazards. In addition, most existing studies use small-sized specimens, with the slenderness ratio generally controlled between 2-3, and the main research object is plain concrete columns. This research setting is far from the reinforced concrete columns in actual engineering, which limits the engineering application value of the research results.

In terms of loading methods, most experimental studies use monotonic axial loading, and the exploration of the performance of BFRP-reinforced SCC columns under cyclic loading conditions is obviously insufficient. However, in actual service environments, structures are often subjected to reciprocating forces such as earthquakes and wind loads. Understanding the structural response under cyclic loading is crucial to ensuring building safety. The few existing cyclic loading studies also have problems such as inconsistent loading systems and scattered test data, making it difficult to form a systematic understanding.

The research gap in numerical simulation is also worthy of attention. Although some scholars have conducted finite element analysis on BFRP-reinforced NC columns, these models cannot be directly applied due to the differences in the material properties and constitutive relationships between SCC and NC. To establish an accurate numerical model of BFRP-reinforced SCC columns, it is necessary to fully consider the special properties of SCC, the interface behavior between BFRP and SCC, and the collaborative working mechanism of the two. Research in this area needs to be carried out in depth.

6. CONCLUSION AND OUTLOOK

6.1 Conclusion

This paper systematically reviews the relevant research on BFRP reinforced SCC columns and reveals the current status and development trends in this field. The study found that SCC, as a new type of high-performance concrete, has been widely used in modern construction projects due to its excellent working performance and construction convenience. However, compared with ordinary concrete, the elastic modulus of SCC is usually reduced by 5%-15%. This difference in material properties makes SCC columns present unique characteristics in structural performance: although the initial stiffness and bearing capacity are slightly reduced, the ductility is improved, and at the same time, it shows certain deficiencies in seismic performance.

In terms of reinforcement materials, BFRP has shown unique competitive advantages in the field of concrete structure reinforcement with its good mechanical properties, excellent environmental characteristics and moderate cost. Compared with traditional CFRP, GFRP and AFRP, BFRP not only has better comprehensive cost performance, but also meets the requirements of sustainable development. Existing research has fully proved that BFRP reinforcement technology can effectively improve the bearing capacity and deformation performance of concrete columns, but unfortunately, research specifically on SCC columns is still very scarce, which seriously restricts the promotion and application of this technology in actual engineering.

6.2 Outlook

Based on the shortcomings of current research and the needs of engineering practice, future research should focus on the following directions. First, it is urgent to carry out BFRP reinforcement experimental research on large-size reinforced SCC columns that is closer to engineering practice, especially to pay attention to the mechanical behavior and failure mechanism under cyclic loads, so as to provide a reliable basis for seismic design. Second, efforts should be made to establish an accurate numerical model of BFRP-reinforced columns that takes into account the characteristics of SCC materials, and to deeply reveal the reinforcement mechanism and the influence of various factors through parametric analysis.

In terms of theoretical research, it is necessary to develop design theories and calculation methods suitable for BFRP-reinforced SCC columns based on experimental and numerical research results, and formulate corresponding technical standards and specifications to provide guidance for engineering applications. At the same time, we should actively promote the construction of demonstration projects, evaluate the sustainability and reliability of the reinforcement effect through long-term monitoring, and comprehensively analyze the economic and social benefits of the technology.

Through continuous efforts in the above-mentioned directions, a complete theoretical system and technical standards for BFRP-reinforced SCC columns will be gradually established, promoting the widespread application of this green and efficient reinforcement technology in engineering practice, and making important contributions to improving the safety performance and extending the service life of existing structures.

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