New Progress in R & D of Basalt Fibres and BFRP in Infrastructure Engineering

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Abstract: The research and application of basalt fibers and the FRP composites (BFRP) have been received much more attention in different engineering fields, especially in civil & environmental engineering and automobile industry, due to its excellent mechanical and chemical properties and high cost performance. This paper reviews the new progress in research and application of basalt fibers and BFRP in infrastructure engineering. Moreover, some new research directions and future application developments on basalt fibers and BFRP are also discussed in the paper.
Keywords: basalt fibres, BFRP, infrastructure, research and application, mechanical performance, green materials

CBF (Continuous Basalt Fiber) is a new high-tech inorganic fiber structure and functional material. It is also a typical energy saving, environment-friendly natural green fiber. It is with carbon fiber, aramid fiber, and high molecular polyethylene fiber becoming China's four high-tech fibers. CBF has many unique excellent performances [1], such as good mechanical properties, excellent temperature performance (it can work under the temperature range of -269 ~ 700 ℃), acid and alkali resistant property, anti-UV property, low moisture absorption, better resistance to environmental corrosion, good insulation, good filtration under high temperature, anti-radiation, sound wave-transparent properties. Composite materials which use basalt fiber as the reinforcing material have been widely used in national defense industry, aerospace, civil construction, transport infrastructure, energy infrastructure, petrochemical, fire protection, automobile, shipbuilding, water conservancy and hydropower, ocean engineering and other fields. There are already many researchs in this area lead by Southeast University, Ibaraki University, Zhejiang GBF Basalt Fiber Co., Ltd. (former Hengdian Group Shanghai Russia&Gold Basalt Fiber Co., Ltd.), and Beijing Texi Da Technology Co., Ltd. [2-4]. This paper outlines the present status and application development of basalt fibers in recent years, especially the new advances in the areas of transport infrastructure construction

1. Introduction

With the development of the continuous basalt fiber industry, the performance advantages of this new material has been fully aware of and gradually accepted. It is becoming a research hotspot in China. Internationally, the research about using basalt fiber as a structural material for the construction of transport facilities is very little. It focus on the following areas: properties research about short chopped basalt fiber reinforced composites [5-6], basic mechanical properties of continuous basalt fiber sheet [7-8], the flexural [8] and sheer properties [9] of concrete beams strengthened by basalt fiber sheet and high temperature performance of basalt fiber plate [10]. However, the current number of papers in these areas is still limited, further in-depth studies and developments are still needed. The current domestic research situation of basalt fiber can be reflected from the papers, patents, applications and specifications published in recent years, as well as degree of government support.

(1) Number of Papers Chart

Along with the development of the basalt fiber industry and its applications, more and more researchers begin to make devotions to the research of the basalt fiber. As can be seen from Figure 1, the number of the domestic published papers about basalt fibers is increasing, especially in 2008, more than 70 papers are published (source: China Knowledge Resource Integrated Database). The pre-published papers are mainly overview articles about the basic properties of basalt fiber and its manufacture. As the development of application of basalt fiber, the published papers began to focus on the areas about basalt fiber reinforcement in civil engineering, transportation infrastructure, researching and development about resin-based composite material. There are more and more application for a patent on basalt fibers (Source: China Patent data network), the early patent is mainly on the basalt fiber manufature technology and now the patent on the application of basalt fibers are more.

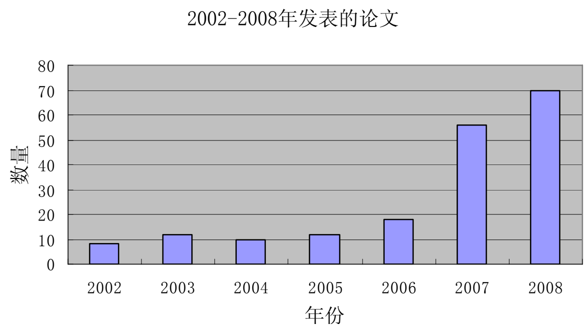


Figure 1 The number of papers published in 2002-2008

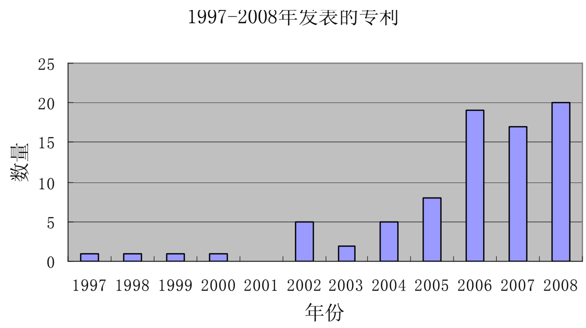


Figure 2 1997-2008 published patent

(2) The Expansion of Research Areas

At present the application research of basalt fiber in civil transport, energy and environmental fields have already had a good development. The application technology of replacing steel or other advanced fiber by basalt fiber based bar, cable, sheet and plate are being recognized and some considerable progress has been made. As the improvement of the basalt fiber manufacture technology and market expansion, developing core application technologies about fiber composite materials in engineering structures such as new type of wind energy facilities, new construction industry (high-performance and long-life of fiber materials and new type of structural system, economic durable and lightweight fiber-reinforced seismic prefabricated civil and industrial facilities, etc.), automotive and aircraft industry as well as the radiation protection of nuclear power facilities, offshore platforms, sub-high-temperature flue gas purification, etc. will become the future research direction.

(3) The Progress of Specification Establishment

As a new material, its development and application must be regulated and standardized by corresponding specifications and codes. At present, the national standard “chopped basalt fiber for cement, cement mortar and concrete” has obtained the permission for publication and will be fully implemented in November 5th, 2009. The manuscripts of two other national standardS (“roving basalt fiber” （20078447-T-609） and “basalt fiber composite material used for structural reinforcement and restoration” （20078383-T-609）) and one technical standard of department (〝Basalt Fibre and its Products of Highway Engineering〞 JT2007-37) will be completed this year. These standards will be served as a regulation for the application of basalt fiber.

(4) Government and AcademicSupport

China government supports the use of basalt fiber at the beginning of its development. In 2002, it was listed as 863 projects. In 2005, two projects ("Application of continuous basalt fiber in weapons and equipment" and “the key technology and applied research of using continuous basalt fibers in a warship") are listed as key basic research projects of State Commission of Science and Technology for National Defense Industry "Eleventh Five-Year" research plan. In March 2007, the National Development and Reform Committee published the "Eleventh Five-year development of chemical fiber industry guidance" has listed the CBF industry as a new high-tech textile industry, which encourages the development of its application. In 2008, Zhejiang GBF Basalt Fiber Co., Ltd. received the national support of an “Annual Output of 2,000 Tons of High-end Continuous Basalt Fiber (CBF) Project”, which is the second government bonds “Textile - Specialty Fiber”

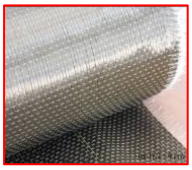
Meanwhile, many domestic well-known scholars began to conduct more systematic research and recommend more government support for basalt fiber industry. Zhi-Tao Lu, Southeast University academician indicate in the “Suggestion for The Construction Province Using Innovation As Support” published in the " Recommendations for the Science and Technology Workers, Jiangsu Province" (2009 No. 1) that "To promote the building and bridge structures innovation, improve the life and safety performance of urban infrastructure in our province, it is recommended to give full play the superiority condition of Lianyungang carbon fiber industry and Southeast University and Hendian Group R&D Center of Basalt Fiber, focus on researching and developing the reinforce and repair technology of buildings and bridges key elements by fiber composite materials, develope fiber composite material which have high durability, draw up the corresponding standard and specification. " Liu Jiaqi Academician of Institute of Geology and Geophysics, Chinese Academy of Sciences published "green high-tech materials---basalt fiber has a broad outlook" [12] on the preface of "Science and Technology Review". This paper pointed out that "China needs to introduce foreign advanced technology, combining with its own practical experience, developing basalt material industry with Chinese characteristics; and it must have higher starting point, broad ideas, and truly consider the overall situation for the country, producing the shortage and much-needed strategic materials. Government departments should attach great importance and strengthen the leadership of research and development of basalt materials, making the disordered state into ordered state ...” In the past five years, two research teams in China and Japan led by Professor Wu Zhishen launched a basic research on the application of basalt fiber in infrastructure, energy-saving environmental protection, aviation and automobiles, published a large number of papers, applied for several patents, and cofounded the Jiangsu Basalt fiber Research Center with Zhejiang GBF Basalt Fiber Co., Ltd. and Beijing Texi Da Technology Co., Ltd.

2. A number of Studies and Application

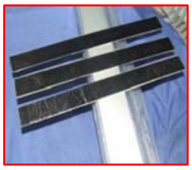
2.1 Basic Research

(1) The basic mechanical properties of a variety of basalt fiber products

(A) Roving

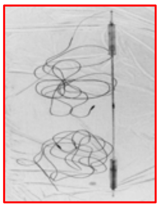


(B) Unidrectional sheet

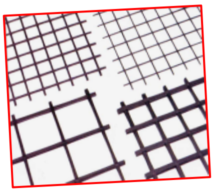


(C) Steel - Basalt Fiber Sheet

(D) SFCB bars



(E) Smart bars



(F) Geogrid

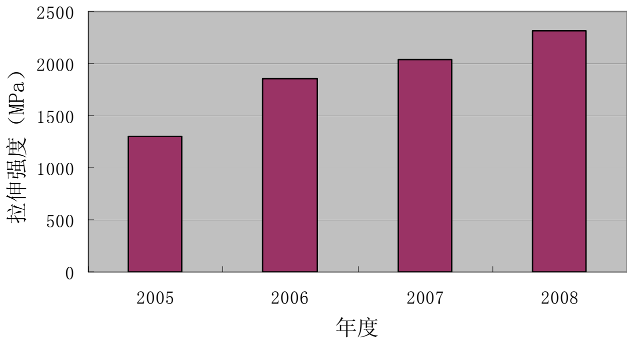
(G) Basalt - Carbon Fiber

(h) -(i) Basalt fiber sandwich structure

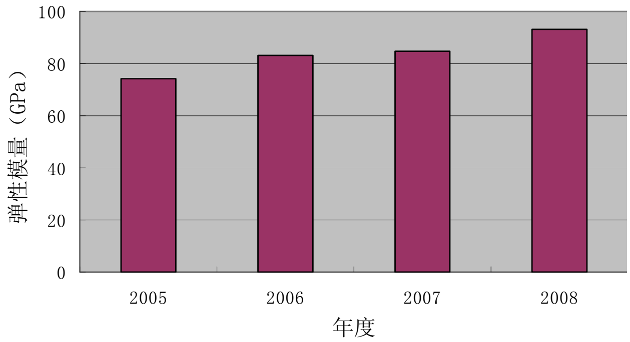
Figure 3 Basalt fiber products

In early days, basalt fibers in civil engineering applications are mainly roving, unidirectional sheet. In the last two years, considering the development trends of composite materials in civil engineering application, the research team developed a variety of new products (Figure 3) like steel-Basalt fiber composite panels, SFCB bars, smart bars, grid, basalt fiber-steel wire composite sheet, basalt and basalt-carbon fiber composite cable, high temperature durable basalt fiber plates, basalt fiber sandwich structure etc. and more products will be gradually developed as the in-depth study.

Fiber sheet is the most widely used form of fiber materials in construction field in the beginning, and the fiber materials’ mechanical properties index can be characterized perfectly by the sheet. Thus, in the past five years, systematic testing has been conducted by the research team about mechanical properties of unidirectional sheet. Figure 4 shows the changes of mechanical properties of basalt fiber unidirectional sheet between 2005 and 2008. It can be seen with the factory production process improvements, the performance of basalt fiber unidirectional sheet is being increased every year, and is likely to further stabilize and improve. At present, the strength properties of basalt fiber sheet is being further improved by using the latest 800-hole melting wire drawing process.



(a) Tensile strength of basalt fiber unidirectional sheet



(b) Basalt fiber unidirectional sheet elastic modulus

Figure 4　2005-2008 mechanical properties of basalt fiber unidirectional sheet changes in trends

Figure 5 compares the basic stress-strain relationship (without regard to matrix material effects) of several major basalt fiber composite materials. It can be seen the initial elastic modulus of basalt fiber composite materials can be markedly improved through the mix of a small amount of carbon fiber or traditional steel wire, in the mean time, the higher limit of basalt fiber strain can still be maintained, which lead to greatly improved overall performance. Basalt fiber composite with reinforced bar will make the SFCB bars not only have higher initial elastic modulus, but also significant post-yield stiffness and good ductility, so that it can not only be used for general structural reinforcement, but also for improving the seismic performance and post-earthquake structural resilience. These developments of new basalt fiber composite materials provide more choices for the basalt fibers in the construction of transport infrastructure.

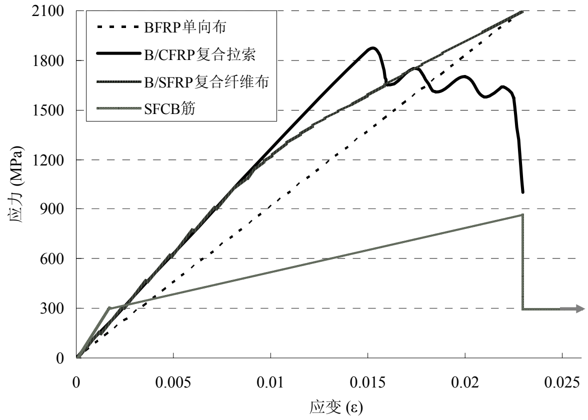


Figure 5　The stress - strain of several basalt fiber composite materials

(2) Fatigue properties of basalt fiber sheet and basalt-carbon fiber composite sheet

As considerable part of the transport infrastructure are under the cyclic loading or dynamic loads, such as bridge decks, large-span bridge girder, road, cable, etc. are subject to frequent the traffic loads and wind loads, and thus the use of basalt fiber and its composite materials in these structures or construction facilities, their resistance to fatigue must be guaranteed. The research team have tested the fatigue performance of basalt fiber sheet under different stress level[13]. The results show that: (1) basalt fiber sheet can be able to cycle 2 million times and not broken under the maximum stress at 55% (amplitude R = 0.1), so it can meet the fatigue performance requirements of the vast majority of civil engineering facilities; (2) Overall, the fatigue resistance of basalt fiber sheet is close to glass fiber, lower than the carbon fiber sheet (Figure 6); (3) the performance stability and fatigue resistance under cyclic loading can be significantly improved through the basalt-carbon fiber hybrid (ratio 1: 1). After mixed, the basalt-carbon fiber composites can maintain the 2 million cycles without fracture (Figure 7) at 70% of the maximum stress (amplitude R = 0.1). This feature makes this hybrid fiber sheet more efficient under the cyclic loading; (4) the basalt fibers and carbon fiber can be bonded well under the cyclic loading, makes the mixed effect more highlighting. In comparison, hybrid effect of glass fiber and carbon fiber is poor, the fatigue strength of hybrid fibers also failed to be improved, as shown in Figure 7.

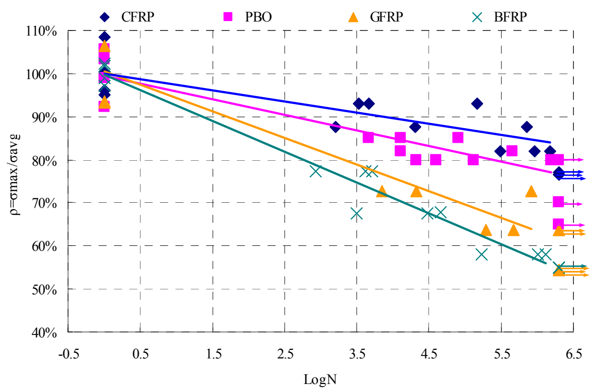


Figure 6　S-N fatigue life (FRP)

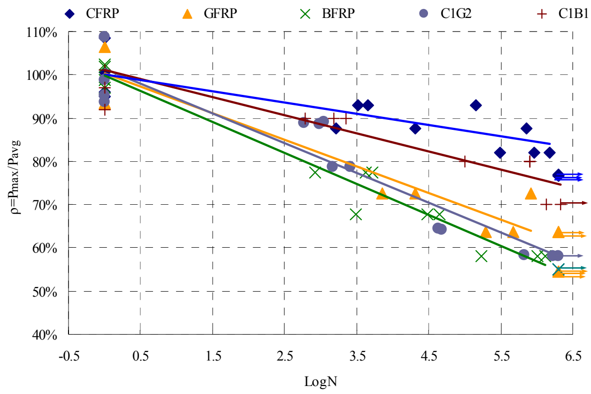
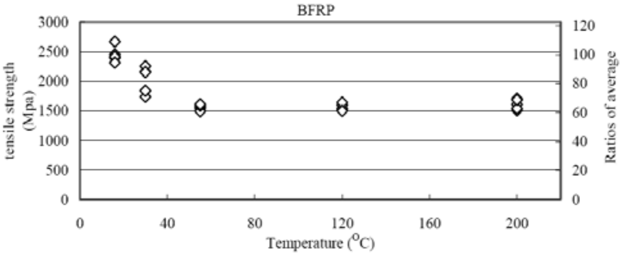


Figure 7 S-N fatigue life (Hybrid FRP)

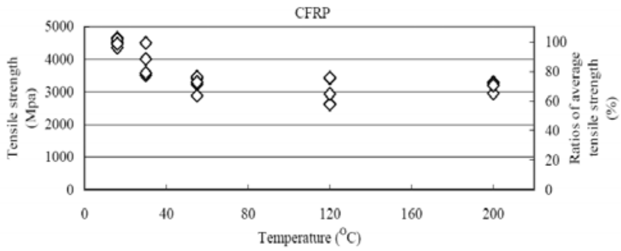
Currently, the research about the hybrid ratio of basalt fiber and carbon fiber and the fatigue property of basalt-steel wire composite sheet are under way.

(3) High-temperature properties of basalt fiber sheet and basalt-carbon fiber composite sheet

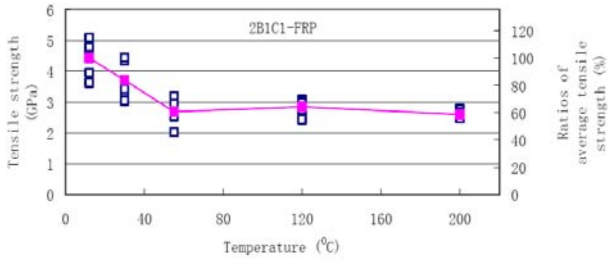
The safety performance of structures under sudden disaster has always been an important topic of concern to the civil engineering, in which the fire is a very common disaster and can make great harm to the structure. Thus, the evaluation of mechanical properties of basalt fiber materials under fire and other high-temperature environment is particularly important. As the basalt fiber itself has excellent high temperature performance (<700 ℃), so the high-temperature properties of fiber composite materials is mainly determined by the high temperature performance of the matrix material. In this regard, the high temperature test for the basalt sheet material, basalt-carbon epoxy matrix composite sheet and basalt fiber bar are performed [14-15]. The tests results show that (1) although the matrix material of basalt fiber sheet has experienced the complete glass transition in the 200℃ heat, (glass transition temperature is 38℃), the composite fiber sheet remained about 65% of the tensile strength (Figure 8 (a), which was significantly higher than the strength of dry fiber sheet (about 50%); (2) although it cannot improve the CFRP tensile strength at high temperatures by mixing basalt fiber and carbon fiber, it can reduce the intensity of dispersion degree of composite fiber sheet at high temperatures, which means the strength value is more stable (Figure 8 (b, c)). (3) While the matrix material of the basalt fiber bar has been vitrified under the temperature of 300℃, the bar is still able to maintain about 85% of the tensile strength, indicating the pultrude fiber material has a better homogeneity (Figure 9). Based on the above findings, in order to ensure that basalt fiber composite materials have a high-temperature performance, it must be ensured that the matrix material of BFRP have good high-temperature performance. The business cooperation with the United States is under way to carry out the basic properties of high temperature durable BFRP materials. It is currently trying to composite the high-temperature phenolic-based resin and fiber sheet, and simulating on-site conservation of viable conditions, testing its tensile properties in the temperature of 200℃.



(a) Basalt fiber sheet



(b) CFRP sheet



(c) Basalt-carbon fiber composite fiber sheet

Figure 8 Tensile strength of fiber sheet in different high temperatures

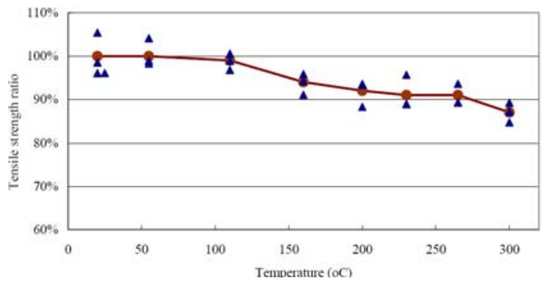


Figure 9 T5ensile strength ratio of basalt fiber bars at different temperatures

In addition, considering the high-temperature performance basalt fiber, the research team is thinking of using the basalt fiber for high-temperature flue gas cleaning and energy saving basalt fiber filter, this area of study is being carried out at present.

(4) Interface property between basalt fiber sheet and concrete

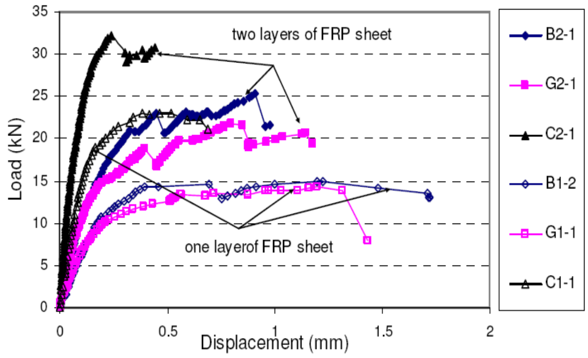


Figure 10　Load - displacement curve of FRP sheet - concrete specimen

External bond is the most basic application form of FRP material in strengthening structure, so the structures' overall performance is greatly affected by the interface property between the strengthening material and the structure itself. Thus, as a basic research, the authors' research team has tested short-term mechanical properties of the interface between the BFRP, CFRP, hybrid fiber sheets and concrete. The results show that the BFRP-concrete sheet has a good load transfer performance, the baring capacity of double layered-BFRP and single layered CFRP are the same when they have same bond length, the CFRP-concrete interface destruction is brittle, while the destruction of BFRP-concrete interface showed a good ductility along with a small sound of rupture as a certain warning. BFRP performance is similar to GFRP and the bearing capacity is slightly higher when there are same layers [16] (Figure 10). Basalt fiber has a higher interfacial fracture energy compared to carbon fibers, as shown in Figure 11. In addition, by mixing BFRP and CFRP, it can improve the mechanical properties of BFRP sheet-concrete interface, and can effectively improve the brittle nature of the interface failure process of CFRP-concrete interface and improve the ductility. Through rational design, basalt fiber and its mixing with carbon fiber sheets can substitute for the carbon fiber reinforced concrete within a certain range structure, its outstanding price-performance advantage can significantly reduce the project cost. This area of research is currently underway.

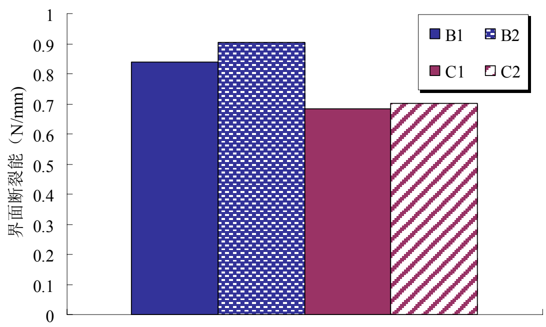
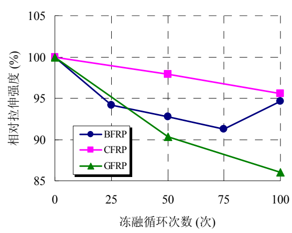


Figure 11 Comparisons of interfacial fracture energy between basalt and carbon-fiber

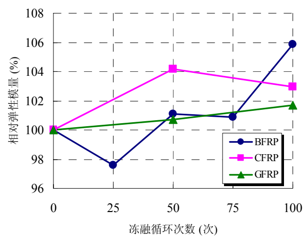
(5) Mechanical properties of basalt fiber sheets in the harsh environment

In order to evaluate the mechanical properties of basalt fiber materials in the harsh environment (such as North China, Northwest Territories, as well as coastal areas), the research team tested the mechanical properties of BFRP sheet under the action of freeze-thaw cycles [17], meanwhile, references [18] tested the mechanical properties of carbon fiber and glass fiber under the same environment, a comparison of three fibers is shown in Figure 12. The results showed that with the growing number of adverse environmental effects, the tensile strength and elongation of FRP sheet have downward trend while the elastic modulus on the rise. After 100 freeze-thaw cycles, the tensile strength of BFRP sheet are the same as CFRP which is much higher than the GFRP sheet; the elastic modulus will be rise by 6%, which is a little bit higher than the CFRP and GFRP; the ultimate strain of BFRP after 100 times of freeze-thaw cycles is still more than 93% of its original and is much higher than CFRP and GFRP.

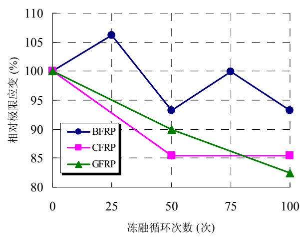
At present, the degradation models of BFRP and BFRP/CFRP under harsh environment are being established.



(a) The relative tensile strength



(b) The relative elastic modulus



(c) The relative ultimate strain

Figure 12 The comparison of BFRP, CFRP and GFRP sheets under freeze-thaw cycles

2.2 Applied Research

Before 2007, the domestic research of BFRP are mainly focus on the structure strengthening area, but lately, the application research of basalt fiber in other areas has a great expansion.

(1) Chopped basalt fiber-reinforced asphalt pavement

With the development of road transport, the traffic volume and axis load increases, so the requirement for the high quality and longer life service time of the asphalt pavement are becoming higher and higher.

As more and more new materials are used in the asphalt pavement technology, adding fiber in the asphalt mixture for enhancing the performance of asphalt mixture is an important tool. Fibers in the asphalt mixture exist in three-dimensional dispersed phase and overlap each other, which can avoid over-concentration of load and improve the overall strength of asphalt mixture; meanwhile, the water stability and high temperature stability of asphalt mixture are improved because of the absorption effect of fiber to the mixture.

The most commonly used fibers in the asphalt concrete pavement engineering are lignin fibers, polyester fibers, mineral fibers and basalt fibers. Basalt Fiber is becoming a highly competitive product comparing to the other fibers because of its good mechanic property and high temperature performance.

Jiangsu Transportation Research Institute and Zhejiang GBF Basalt Fiber Co., Ltd have performed the rutting tests and Marshall Test on basalt fiber and polyester fiber asphalt mixture [19]. Figure 13 and Figure 14 show that the anti-water-damage performance of BFRP asphalt mixture is slightly higher than the polyester asphalt mixture and the asphalt mixture, and the high-temperature stability is improved significantly

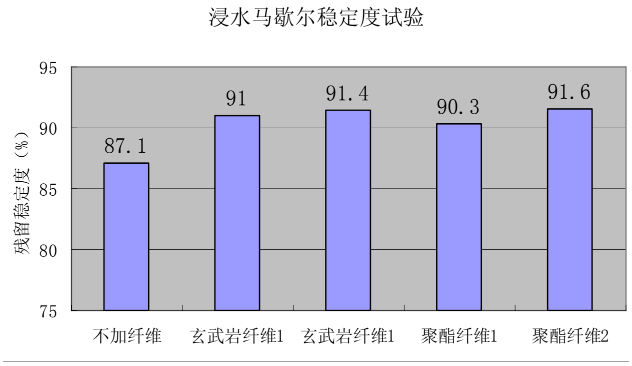


Figure 13 Soaking Marshall Stability test

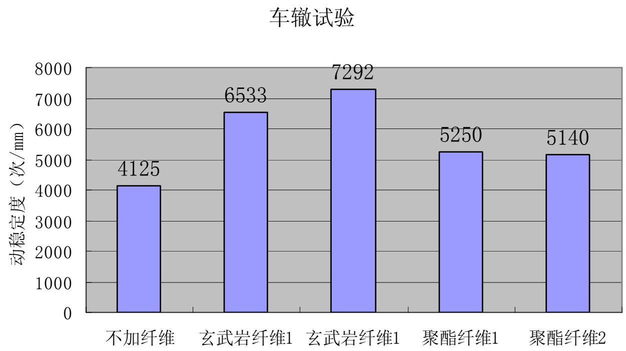


Figure 14 High Temperature Stability Test

Recently, Hangjinqu Highway K143 +512 ~ K144 +141 section use basalt fibers made by of Zhejiang GBF Basalt Fiber Co., Ltd. to strengthen the AC-13 modified asphalt concrete, and carried out overlay conservation tests. After overlay construction, the overall conditions of these sections are good such as no oil on the surface and no loose phenomenon. Based on the core taken from the onsite condition, the compaction degree are up to 99%, the water permeate coefficient and anti-slip value can all meet the specification requirement. Using the basalt fiber modified asphalt concrete AC-13 to deal with the road maintenance can improve the conservation quality and service life of the pavement, which result in low afterward maintenance costs and great economic benefit.

(2) Chopped basalt fiber reinforced concrete

The basalt fiber can be used in the tunnel and underground engineering by taking advantage of its high strength and fire proof properties. Southwest Jiaotong University and Zhejiang GBF Basalt Fiber Co., Ltd. conduct the research about the basalt fiber shotcrete [20]. It has been proved that the basic mechanic properties of the basalt fiber shotcrete have met the quality requirement of concrete. The compressive strength, the shear strength and the flexural strength have all been greatly improved comparing to the plain concrete. The impermeability coefficient of the basalt fiber concrete and the basalt fiber composite concrete are all achieve the level S12. The shotcrete tests show that the basalt fiber have an obvious effect on the rebound of steel fiber, it reduces the rebound rate and improve the utilization rate of the steel fiber in the shotcrete. The project researcher believes that the basalt fiber with length range of 20~25mm and diameter range of 18~22μm and the steel fiber can be applied in the tunnel lining through optimized combination. It is recommended that during the design and construction process, the volume of basalt fiber and steel fiber should be choose by considering the onsite geological environment and load condition. If you want to increase the toughness results, we recommend adding an appropriate amount of steel fiber.

Basalt fiber can be used as a construction material to delay the crack propagation due to the early shrinkage, and the compatibility between the concrete and basalt fiber is very good. Unlike the steel fiber, the basalt fiber in the concrete will not affect the insulation property of the prestressed concrete; also it will not corrode like steel fiber, which makes the basalt fiber an ideal admixture to the Ballastless track slab. There are two slabs already been used in the Passenger Dedicated Line from Wuhan to Guangzhou and they have participate in the on-site condition test from 2008 [21] as show in Figure 15.

Figure 15 Ballastless Track plate in Wuhan section of Wuhan-Guangzhou passenger line

(3) Basalt fiber composite bars

The elastic modulus of the basalt fiber composite bars (BFRP bar) is low (currently about 40GPa), but it has some obvious advantage in some application areas due to its low price, non-rusty, electrical insulation, non-magnetic, acid and alkali resistance properties [22]. For example, in 2007 in order to meet the seismostation's non-magnetic requirements, Lanzhou Seismological Bureau uses basalt fiber composites instead of steel bars in the construction of seismostation (Figure16). Southeast University developed the bending manufacture technology in order to solve the reinforcement bending and stirrup making problem. The seismostation works well at present.

Figure 16 Applications of basalt fiber composite bars in Lanzhou seismostation

In May 2008 the Southeast University, Zhejiang GBF Basalt Fiber Co., Ltd. and Zhang Shi

Shijiazhuang expressway management jointly develop a continuous reinforcement construction technology using basalt fiber composite reinforcement to enhance the road, taking north and south ends of the Xingtang Bridge for the trial (Figure 17). This continuous reinforcement construction technology achieve a truly non-welded contact, reducing the shrinkage cracks of the concrete blocks, it also resolve the corrosion effect of the de-icing salt to the steel reinforcement, which improve The quality and durability of highways and reduce highway costs, shorten construction time.

Figure 17 The application of basalt fiber composite bars on the highway

(4) The self-monitoring smart basalt fiber reinforcement

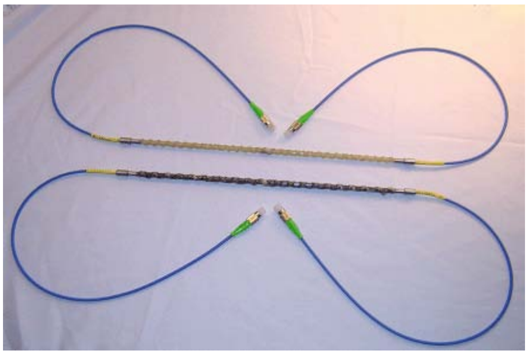


Figure 18 BFRP smart bars

The self-monitoring smart basalt fiber reinforcement is showed in Figure 18; its construction is to put the distributed sensing optical fiber in the manufacture process of the basalt fiber bars which make the bar as a self-monitoring, self-diagnostic new smart material. The stability and durability and its mechanic property of this smart material can adapt to the harsh serving condition of bridge, pavement and tunnel, it can provide an effective monitor and evaluation for the safety operation of these transport facilities[23 -- 24].

We bury the smart bars in concrete beams and monitor the structure state during the whole serving life time (static load tests). Figure 19 shows the strain distribution along the bar after beam bottom cracked, the result fit with the experimental phenomena, the strain peak appears at the cracks. As shown in Figure 20, in the reinforced concrete pavement, smart bars can effectively measured contraction deformation within 28 days after pouring concrete day and sensors in the structure have been able to work stable after structure forming. The smart bars are also expected to apply in monitoring the performance of asphalt concrete pavement. At the same time, the research team will use the smart bars to monitor the deformation of hoop and longitude direction of the tunnel by embedding the smart bars at these directions. It provides a new thought of how to solve the monitoring hardness under complex geological environment.

At present, the intelligent monitoring system for a city's cross-river tunnel based on the use of BFRP smart bars is completed design as shown in Figure 21.

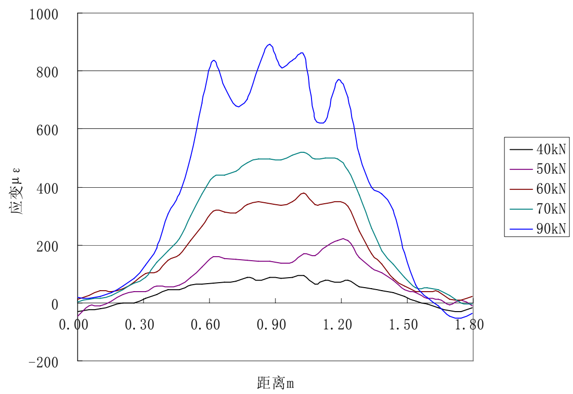


Figure 19 Application of Intelligent bars in concrete beams

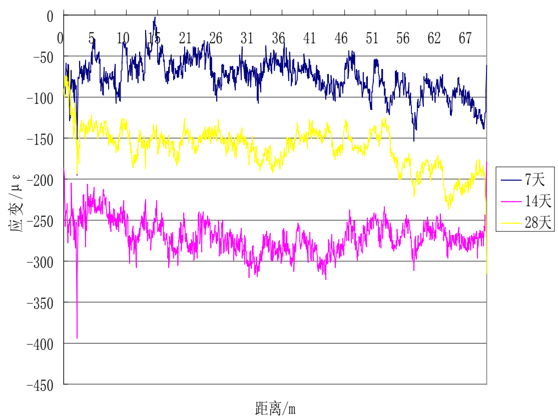


Figure 20 Application of Intelligent reinforcement bars in concrete pavement

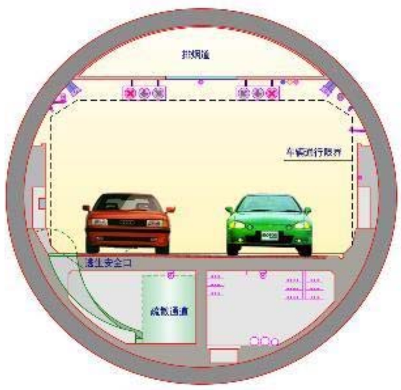


Figure 21 Application of intelligent reinforcement in the concrete tunnel

(5) Composite cable based on basalt fiber

To meet the world wide need for large span bridge over the gulf or river like the Su-Tong Bridge, Hong Kong Stonecutters Bridge, Qiongzhou Strait projects, Messina Strait Bridge (Italy), Gibraltar Straits Bridge (Spain, Morocco), etc., it has become a research hotspot that how to use the advanced FRP material as a substitution for the traditional material. The research team proposes the use of basalt-carbon fiber composite tendon as a replacement of the traditional steel strand as to achieve the economic goal. Traditional steel wire (strand) will affect the overall performance of bridge because of its shortcomings like large weight and is prone to corrosion when in the span of 1,000 meters. Some scholars proposed that using carbon fiber tendon can solve above problems, but the large-scale application is limited because of its high price. Also, the carbon fiber tendon is more sensitive to the wind activity because of its high strength and low density. Based on this, the research team put forward of using basalt-carbon fiber composite cable to achieve the high performance. The research results indicate that: (1) the basalt-carbon fiber composite cable in the 1000m span cable-stayed bridge can achieve the excellent static and dynamic performance like CFRP cable but the price costs only 68%[25-26] (Figure 22, 23); (2) the aerodynamic stability performance of the basalt-carbon fiber composite cable is more superior than the CFRP cable, also we can increase the cable's damping to achieve the smart performance like self-damping by section design based on the different attributes of two fibers to the cable [27] (Figure 24,); (3) the self-damping cable shows lower resonance amplitude and stress amplitude under indirect incentives comparing to the carbon cable and steel cable, which is good for the safety and long-term performance of the cable [28] (Figure 25).

In addition, the research team has also developed a basalt fiber-steel wire composite cable which is suitable for lower than 2000m span, the composite cable have a better performance-price ratio. The author also analyze and evaluate the suitability of four types of cables in the span range under 10,000 meters including two composite cable mentioned above and pure basalt fiber cable and carbon fiber cable based on the utilization ratio of each materials [29] (Figure 26). Meanwhile we can make the composite cable intelligent by embedding the distributed optical fiber in it. The design is of great importance to the real-time monitoring and real-time control of cable under traffic load and wind load (Figure 27).

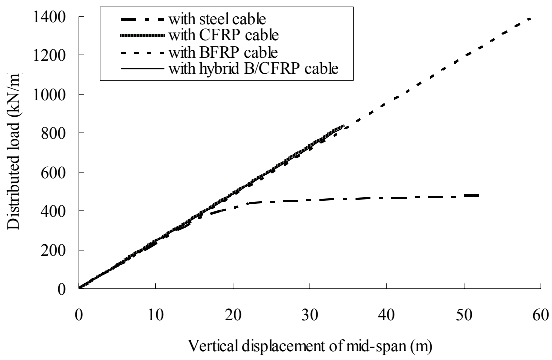


Figure 22 Static performance of 1000m span cable-stayed bridge

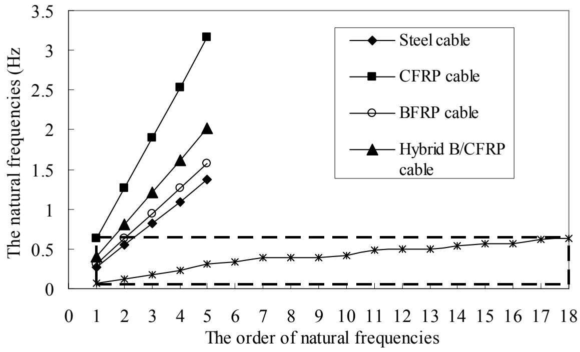


Figure 23 Resonance of the longest cable and the deck of 1000m span cable-stayed bridge

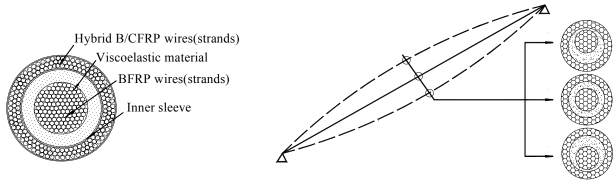


Figure 24 Self-damping basalt - carbon fiber composite cable design

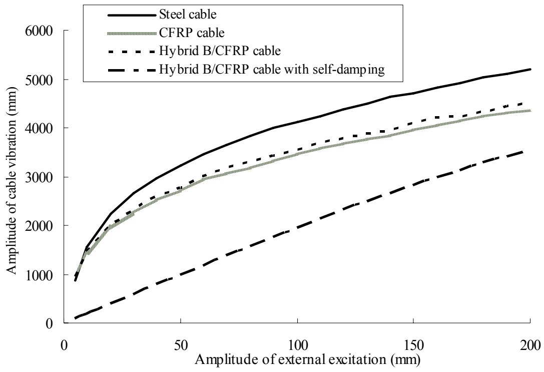


Figure 25 The amplitude response of cable under outer excitation

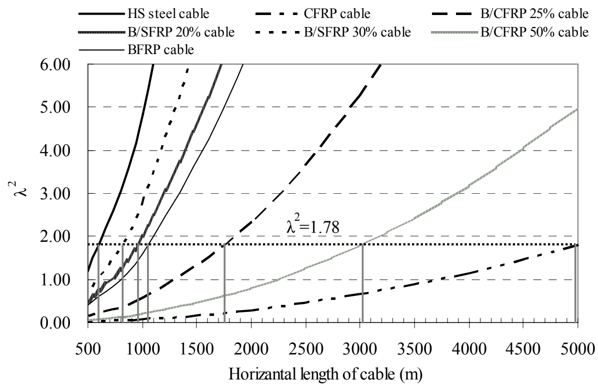


Figure 26 Fitness evaluation of a variety of basalt fiber based composite cable

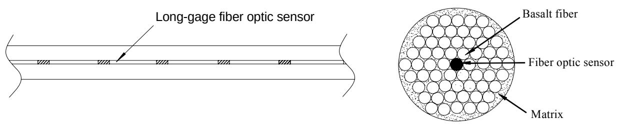


Figure 27 Smart composite cables

(6) Basalt fiber unidirectional sheet

① For structural seismic reinforcement

Because the priority concern of seismic structure strengthening is ductility rather than strength and stiffness, so basalt fibers have a unique advantage comparing to the carbon fiber sheet in this aera. The research team performed comparison test between BFRP wrapped column and CFRP wrapped column [30]. Figure 28 shows the testing hysteresis curve of one column with no strengthening technology and one with 2.5 layers of CFRP wrapped around and one with 4.5 layers of CFRP and one with basalt fiber bundle circle around the column, they are represented by S-0, S-2.5C, S-4.5C and S-BF respectively. The tests results show that the column strengthened by basalt fiber bundle shows much higher of shear strength comparing to the others, the basalt fiber bundle can also change the failure mode of the column. Under the similar lateral restraint stiffness, the continuous basalt fiber strengthened columns can achieve the same or higher strength, energy dissipation and ductility but lower price than CFRP strengthened columns. So the BFRP material is more suitable for structure strengthening for higher seismic performance.

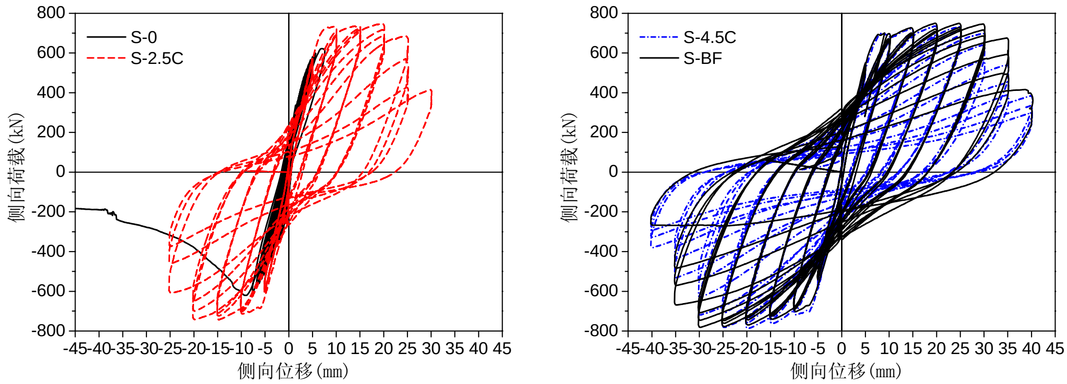


Figure 28 Comparison of hysteresis curves before and after strengthening

② Prestressed strengthening

Since most of the fiber material has lower elastic modulus than steel, and also the steel structures have already been under load condition before strengthening with FRP sheet, so the strength of the FRP cannot be fully used because it only deformed with the original structure under secondary loads, which result in material waste. Based on this, we put forward the prestress technology of FRP sheet in order to improve the material utilization ratio. The fiber sheet without impregnate the matrix has low tensile strength, so the applied prestress cannot be effectively imposed on the structure. If the sheet is impregnated in the matrix material, the fiber sheet is difficult to attach to the structure because of its curving surface after matrix drying. To solve this conflict and improve the utilization efficiency of fiber sheet, the research team proposes the dry mixture of carbon fiber and basalt fiber to form a new composite sheet in order to achieve the high strength tensile of dry hybrid fiber [31-32] (Figure 29). We tested and compared the different hybrid ratios; the results show that tensile strength of carbon fiber sheet increase from 30% to 54% of the dry fiber, which guarantee the implementation of high prestress on the fiber sheet. With this method, we have a beam flexural strengthened with one layer of basalt fiber plus three layers of carbon fiber which endure 33% of the tensile prestress of dry fiber. The results are shown in Figure 30, we can see that the prestress play an important role in improving the strength and post-stiffness of structure.

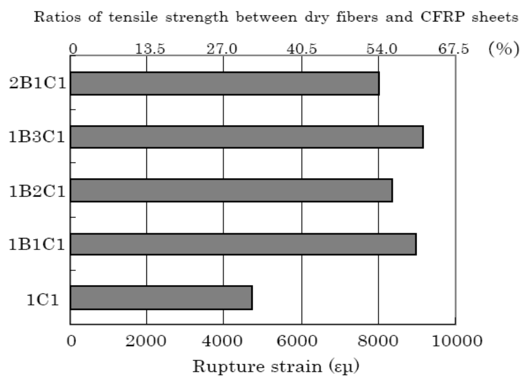


Figure 29 Tensile strength of the 2 meters long fiber cloth without impregnation

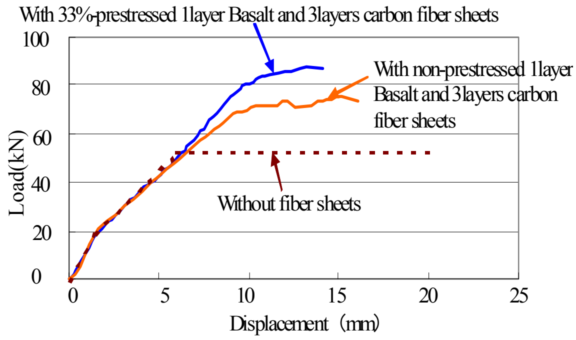


Figure 30 The Lord-displacement curve of prestress strengthened beams

Basalt fiber sheet can achieve the prestressed tension by not only hybridizing with carbon fiber sheet but also by compositing with steel wire which have a small diameter (piano wire), which will also improve the overall stiffness and the cost will not increase much[32] (Figure 31). As shown in Figure 32, the stiffness of two layers of basalt fiber sheet can be significantly improved to like three layers by compositing 20% of piano wire in volume. The tests on the beams prestressed strengthened with this type of basalt-steel wire composite sheet show that the crack load and yield load are both increased as show in Figure 33.

Figure 31 Wire - Basalt fiber unidirectional sheet composites

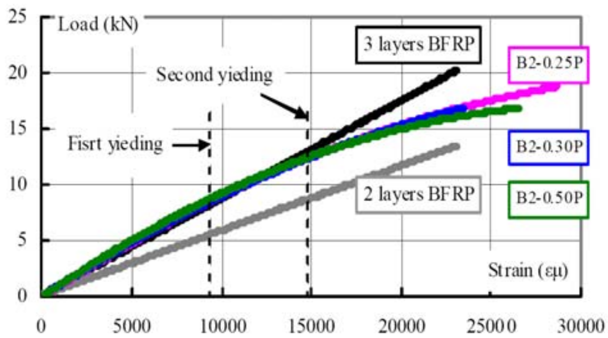


Figure 32 The Lord-displacement curve of basalt fiber - steel wire hybrid cloth

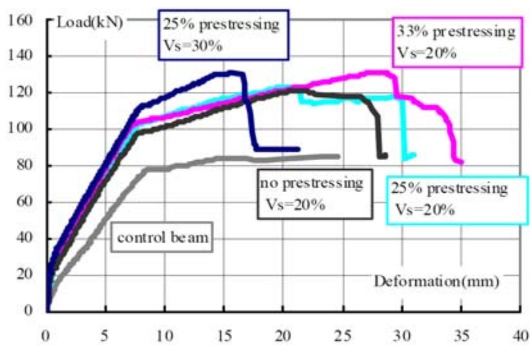


Figure 33　Beams prestressed enhanced with basalt fiber - wire hybrid sheet

(7) Steel-continuous fiber reinforced composite SFCB

The research team develop steel fiber composite bar which has higher comprehensive performances comparing to FRP which have high strength, low elastic modulus, poor ductility, good durability, light weight and steel bars which have low strength, high elastic modulus, good ductility, good durability, heavy weight [33-36]. (Figure 34).

Figure 34　Steel - continuous fibers composite bar SFCB

For the SFCB, the author noted that the combination of linear elastic FRP and elastic-plastic steel can lead to changes on the mechanical properties and we can reasonably making use of these changes in practical engineering application. The post-cracking stiffness, yield load and post-yield stiffness of beams reinforcement by SFCB have a significant increase (Figure 35). SFCB have stable secondary stiffness, which can be used to build structures which is damage controllable and have high post-earthquake reparability. Figure 36 shows the hysteretic curve of SFCB strengthened columns under cyclic load, it can be seen that comparing to the regular RC column, the SFCB strengthened columns shows obvious secondary stiffness and smaller residual deformation after remove the load, these two characteristics are of great importance to the energy dissipation, damage control and post-earthquake recovering abilities of the building.

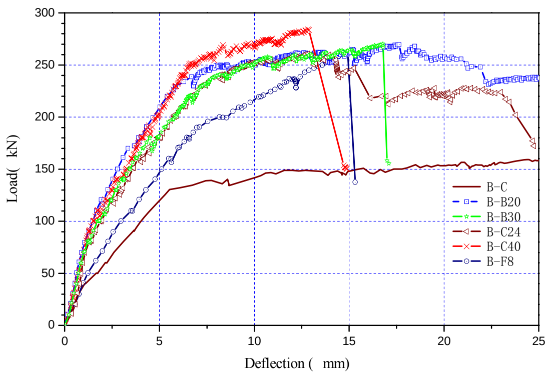


Figure 35　The Lord-displacement curves of SFCB strengthened beams

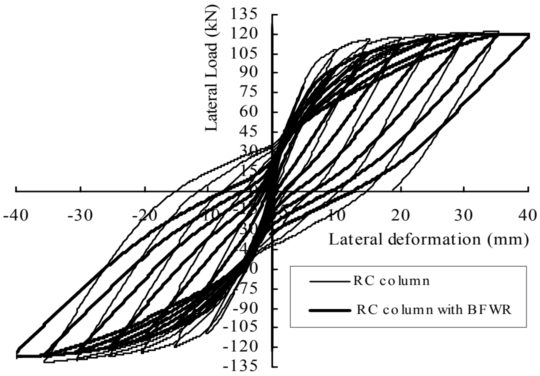


Figure 36　The load - displacement hysteresis curves of SFCB strengthened beams

(8) Basalt fiber composite profiles

The fiber sheets are normally used for the reinforcement of the existing structures; however, the fiber profiles are more suitable for the construction of the new structure. Profiles not only have fixed shape which can be used as structural templates, but also through the use of wet-bonding techniques, it can effectively guarantee the reliable bond between fiber profiles and structure, allowing fiber profiles to achieve full strength, improving the bearing capacity of the structure of guarantee ductility [37-39]. Based on this, we have research and develop the T-shaped basalt-carbon fiber-concrete composite beam (Figure 37). The tests results show that (1) comparison results of several bonding methods, such as wet bonding, dry bonding and pre-bonded gravel, show that each bonding method can achieve very good results, in which wet-bonding approach not only good results, but also facilitate the rapid construction (Figure 38); (2) the composite beams have obvious secondary stiffness after yielding of the longitudinal reinforcement and the ultimate load are greatly improved; (3) the hybrid of CFRP and BFRP improve the ultimate strain value of CFRP, and the more layers of BFRP, the more obvious this phenomenon (Figure 39). The material utilization efficiency is improved.

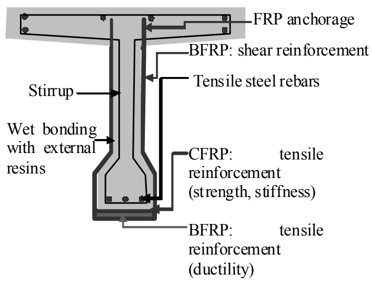


Figure 37　Fiber profiles - concrete composite beam

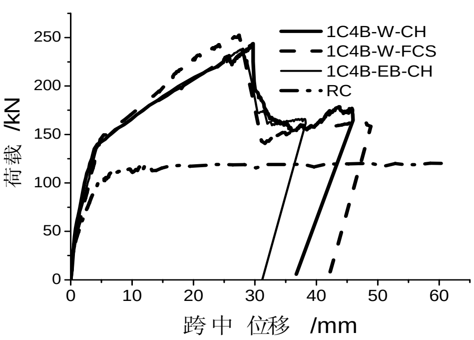


Figure 38 Different bonding methods

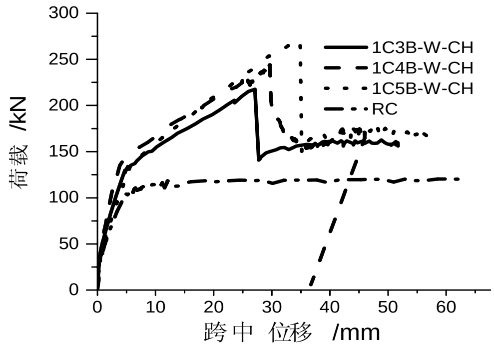


Figure 39 Bearing capacities of composite beams with different layers of basalt fiber

(9) Basalt fiber sandwich structure

The problem of structures facing impact and explosion is becoming more and more prominent. There is a need to develop new materials and new structures with integrated high performance. It is not the best to rely solely on increasing the structure size to improve its disaster preparedness, the use of porous lightweight materials in design of the structure has become a research hotspot in explosion area. The currently most typical porous lightweight material is the sandwich structure. Sandwich structures are usually composed by upper panel, core material and down panel. The panel materials require for good stiffness and strength, the commonly used materials are FRP, aluminum, steel, concrete etc. The basalt fiber used as the panel has a low price, light weight, good adhesion, and excellent corrosion resistance etc. the research team propose basalt fiber reinforced polymer-lightweight aerated concrete (BFRP-ALC) sandwich structure. This new type of sandwich structures can be widely used in not only field fortification, civil air defense engineering and defense engineering, but also in bridge engineering, industrial and civil construction and other fields. The research team has already conducted preliminary testing and verification; the results are satisfactory [40].

Figure 40 Basalt fiber sandwich structure

3 Summary and Recommendations

This paper summarizes the recent application and research of basalt fibers in the field of transport infrastructure made by the research team led by author, and made clarification about basalt fiber as a material which have excellent compatibility with matrix resin. It can hybrid with steel wire, steel bars, or other fibers materials and show a prominent mixed effects which include short-and long-term mechanical properties, fatigue resistance, high temperature performance, good performance/price ratio of using the shot chopped basalt fiber. The basalt fiber composite materials also have great performance/price ratio in general strengthening and prestressed strengthening of concrete structure. In addition to the general structure reinforcement, basalt fiber sheet and its reinforced composite material is also able to play an important role in displacement control of structures under earthquake and its post-earthquake recoverability; In addition, the basalt fiber composite cable has more advantages and broader prospects in the 1000 meters in-span cable-stayed bridge. Based on the above study, there are some thoughts and recommendations on the future development as follow:

(1) Accelerating the development of new basalt fiber products

In order to be better and faster in promoting a wider field of using basalt fibers, we must accelerate the research and development of basalt fiber products to improve the basalt fiber problems and gaps, thereby promoting faster to further reduce the price of basalt fibers

(2) Strengthening the research of the basic mechanism properties

Currently, the application of basalt fiber is in precede of basic research, in order to have a better and more scientific application of basalt fibers, we must strengthen the system analysis of the short-term, long-term, static, dynamic, extreme environments (high temperature, low temperature , chemical corrosion, freezing and thawing, etc.) properties of basalt fiber and its composite materials and establish the corresponding theoretical model and design methods to guide the practical application.

(3) Ordering

Government departments and industry associations must strengthen the organization and order the producing, research and application of basalt fiber, which can be achieved through supporting the research subject, establishing various standards and various types of R & D centers

(4) Rational use of basalt fibers

Basalt fiber has its many advantages, but there are shortcomings too. We should propagate objectively and use dialectically. We must systematically compare the strength and weakness of BFRP and CFRP, GFRP and AFRP, make full use of its advantages in engineering applications, and can ensure its healthy development by using advantages complementary between the different fibers

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