ADVANCEMENT OF STRUCTURAL SAFETY AND SUSTAINABILITY
WITH BASALT FIBER REINFORCED POLYMERS
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Abstract: Basalt fiber composites (BFRP) have been receiving increasing attention in civil infrastructures, due to their excellent mechanical and chemical properties and high cost-performance. This paper reviews the recent achievements in advancing structural safety and sustainability by BFRP composites based on the research conducted by the authors’ research team. The major research consists of the advancement of basalt fibers through enhancing production techniques, the fundamental study of BFRP under static and cyclic loading, high temperature and severe environment and the common application directly by BFRP products. To further pursue the advantages of BFRP and its application in safe and sustainable structures, the advancement of BFRP composites through hybridization with other materials is also addressed. Based on the advancement in BFRP composites, the innovative application techniques of BFRP in civil infrastructures are further introduced, including smart structures with BFRP smart bars, long-span bridges with hybrid BFRP cables, the prestressed concrete structures with pre-tensioned BFRP sheets, damage controllable and recoverable structures with SFCB, and the sustainable structures with BFRP profiles. Finally, some new directions of research and future application for the enhancement of structural safety and sustainability are proposed.

Keywords: basalt fiber, FRP, safety, sustainability, advancement

1. Introduction
In recent years, increasing attention has been paid to structural safety and sustainability, which includes structural durability, the lightweight requirement, the recoverability after disasters and the related economical and recyclability issues. For instance, a steel truss bridge on (I-35W), with only 43 years of service, in Minnesota USA collapsed entirely in 2007\textsuperscript{[1]} due to the fatigue and corrosion of a joint; the self-weight accounts for 85\% of the total stress in structural members of high-rise buildings; the financial losses due to corrosion of structures by ocean water reaches 700 billion USD globally and 100 billion USD for China every year\textsuperscript{[2]}; and it is reported that the steel mine reserve in China is only 11.5 billion tons, but the exploitation is reaching more than 0.6 billion tons each year. All these problems which pose a potential crisis, indicate that the durability of structures need to be greatly enhanced and in order to improve structural safety keep, and the self-weight of structures should be lowered to reduce stresses in structural members and to extend the structural lives, and the recoverability of structures should be improved in order to ensure quick recovery of major constructions after large disasters such as earthquake and blast.

To address the solve above problems, a promising solution is offered by using fiber-reinforce polymer (FRP) composites, which have clear advantages such as high strength, light weight, good resistance to fatigue and corrosion, ease of forming, and etc, in comparison with steel elements\textsuperscript{[3-5]}. Partial or complete adoption of FRP composites as structural members can significantly enhance structural safety and sustainability. Effectiveness of this approach has been widely demonstrated in the world within the last thirty years. Basalt FRP (BFRP) is the latest FRP composite that has developed within the last ten years and has been...
proven to have advantages in achieving the goal of enhancing safety and reliability of structural systems compared with the conventional carbon, glass and aramid FRP composites. CBF (Continuous Basalt Fiber) is an inorganic fiber and functional material. It is also a typical energy saving, environment-friendly, natural green fiber. Along with carbon fiber, aramid fiber, and high molecular polyethylene fiber, CBF is becoming China's fourth high-tech fiber. CBF has many unique excellent behaviors\textsuperscript{[1]}, such as good mechanical properties, a wide-range of working temperature (-269\textdegree{C} to 700\textdegree{C}), acid, salt and alkali resistance, anti-UV, low moisture absorption, good insulation, anti-radiation, and sound wave-transparent properties\textsuperscript{[6]}. BFRP composites have begun to be used in national defense industry, aerospace, civil construction, transport infrastructure, energy infrastructure, petrochemical, fire protection, automobile, shipbuilding, water conservation and hydropower, ocean engineering and other fields.

![Fig.1 Stress-strain relationship of different FRP](image)

BFRP shows advantageous characteristics in mechanical, chemical and high ratio of performance to cost in comparison to CFRP, GFRP, AFRP, steel bars, and etc, as shown in Fig.1. For instance, BFRP has a higher strength and modulus, a similar cost, and more chemical stability compared with E-glass FRP; a wider range of working temperatures and much lower cost than carbon FRP (CFRP); over five times of strength and around one third of density than commonly used low-carbon steel bars.

Due to above advantages, BFRP has already become an attractive alternative for replacing conventional construction materials and is expected to enhance structural safety and sustainability. However, although BFRP has potential advantages, as mentioned above, the fundamental studies and the relevant applications are still limited due to the relatively recent development compared with other FRP composites. Focusing on identifying the deficiencies, the authors’ research team has conducted a series of studies to develop a more in-depth understanding of the fundamental behavior, the strengthening mechanism, and the application technologies of BFRP composites. In particular, herein some enhancement techniques, which are used for improving the properties of BFRP are studied with regard to structural safety and sustainability requirements. In this paper, the fundamental studies on basalt fibers and BFRP are first summarized; the practical applications of BFRP in civil infrastructures are then introduced; the progress in BFRP with a focus on structural requirements is further addressed. Finally, some key and innovative application technologies for achieving high-performance and durable structures are presented.

2. Fundamental study of basalt fibers and composites

2.1 Basalt fibers\textsuperscript{[6-7]}

Although basalt fibers and composites have potential advantages for application in construction, compared with conventional structural and the other fiber materials, there are several issues and major challenges that
still limit their further development and applications. Among these are **stability, ability of large scale production, lack of high-end products and special types of basalt fibers**. The stability of the mechanical properties of basalt fibers is the most important issue, because the unstable properties greatly lower the utilization efficiency leading to a waste of material and subsequently, limited applications in engineering. Due to this present limitation, the basic requirement for basalt fiber sheet is a strength larger than 2000 MPa and the CV less than 5%. The mass production is also a key factor for lowering the cost and thus, widening the application fields of basalt fibers, which is currently limited by the production equipment and the related production technologies. Basalt fibers should not only be regarded as a superior replacement of glass fibers, but it is also possible to develop high-end basalt fibers that can exhibit similar behavior to carbon fibers (T-300) in order to meet different structural requirements. Meanwhile, it is possible to develop special types of basalt fibers for hazard mitigation and extreme condition applications, such as high-temperature (fire) resistant structural materials, materials for severe environments (acid, alkali), and other structural engineering applications that require a high level of safety, risk mitigation and reliability. To overcome the barriers that currently limit the utilization of Basal Fibers to be utilized in such wide range of applications, a series of studies is currently on-going with a focus on the production process of basalt fibers as shown in Fig. 2 [5].

The first is the development of the proper technology for mineral selection. It should be mentioned that CBF requires strict chemical and mineral compositions, and thus, not necessarily any Basalt mine can be used to produce CBF. Thus, the mineral selection technology is the base for producing basalt fibers. This is currently limited due to the following bottleneck problems: high temperature of devitrification, fast speed of revivification and cooling, narrow temperature range of fiber formation, and high content of Fe, and poor diathermancy of melting. At present, the technology development is studied through investigating chemical and mineral composition.

The second is mineral melting and drawing technology. In order to obtain homogeneous melting, an automatic feeding device was developed by this research team to precisely control the feeding of basalt and to avoid shortcomings of hand feeding. A level controller was designed to optimize the melting process. By
utilizing this approach, intelligent monitoring and control technology can be realized. Due to the importance of bushing plate, lubricator, gathering roll and traverse unit, their positions greatly influence the stability of drawn fibers. Thus, a series of parameters that control the positions were studied, which resulted in an optimization of drawing technology and the enhancement of the quality of basalt fibers.

The third is the surface treatment (sizing) technology. The surface treatment through film forming agent, lubricant, coupling agent will greatly influence the behavior of fibers and the matrix. The studies were conducted according to the certain requirements of construction such as the behavior under elevated temperatures and bonding behavior of fibers and matrix under corrosive environment. Now, the lack of high performance sizing raw material is a limitation to improve surface behavior.

The fourth is the mass production technology. To realize massive production and subsequently lower the cost, a transition from single crucible furnace to tank furnace was studied. The optimization of the electrical furnace, the design and development of electrical-gas furnace and large-scale bushing (800 -1600-hole drawbench bushing) are the key issues.

Through above studies, the mechanical and chemical properties of basalt fibers can be enhanced based on the application requirements, which means the structural performance can be designed and controlled the level of source materials first. The above studies will provide wider and more flexible choices of basalt fibers for structural application.

2.2 Basic properties and regular applications of BFRP

2.2.1 Types of BFRP products

To satisfy different structural applications, various types of basalt FRP products were developed in the recent years. The basalt fiber roving (Fig.3(a)), unidirectional sheets (Fig.3(b)) were first developed and widely used. In the last six years, the research team developed a variety of basalt FRP products \[^8\] (shown in Fig. 3) such as (c) grids, (d) laminates, (e) bars, (f) profiles, and some advanced products including (g) smart bar embedded with fiber optic sensors, (h) steel-fiber composite bar (SFCB), (i) fiber-steel wire FRP plate, (j) hybrid FRP tendons, (k) high temperature durable FRP plates, (l) basalt fiber sandwich structure member etc.

2.2.2 Basic mechanical properties

The typical mechanical properties of basalt fiber sheets are shown in Fig.1, in which the strength and the elastic modulus of basalt fiber sheets have increased over the recent years by improving production technologies (Fig.4), and have reached around 2100 MPa and 90 GPa at present. The strength and modulus are 1350 MPa and 55 GPa, for the basalt FRP tendons with vinyl ester, and 1500 MPa and 50GPa for the tendons with epoxy resin. The strength of BFRP grids is larger than 1000 MPa compared with GFRP grids.
with 600 MPa and CFRP grids with 1400 MPa.

Fig.4 Mechanical properties of basalt fiber sheet between 2005-2010

2.2.3 Fatigue properties of BFRP

As considerable civil and transportation infrastructures are under the cyclic or dynamic loads, for instance, the bridge decks, large-span bridge girders, roads, cables, etc. are subjected to frequent traffic loads and wind loads, thus, the use of FRP materials in these structures or construction facilities, requires that their resistance to fatigue must be guaranteed to meet the safety requirements. The research team tested the fatigue behavior of BFRP sheets under different stress levels [9]. The results show that BFRP sheets are able to maintain the maximum cyclic stress of 55% (amplitude R=0.1), without fracture, subjected to two million cycles of loading. So, in general, the fatigue strength of BFRP can meet the requirements of the majority of engineering facilities.

Fig.5 Modules degradation with cyclic loading

In addition to fatigue strength, a change of the tensile module of BFRP is recorded in the experiment as shown in Fig.5. The damage represented by the reduced modulus was permanent. The fatigue failure of tested sheets, thus, occurred when the total accumulated damage reached a critical limit. Although there were notable scatters in the modulus reduction, the critical limit was approximately 75% to 90% of the initial modulus of BFRP sheets. Thus, the reduction of elastic modulus of BFRP should be further investigated to ensure structural deformation requirements.

2.2.4 Tensile properties of BFRP under elevated temperatures

The structural safety under sudden disaster, such as fire which is a commonly occurring disaster, is always an important topic of concern in civil and transportation engineering.. In comparison to conventional structural materials such as steel and concrete, BFRP composites are relatively weak in resisting high temperature. Thus, it is extremely important to design a structure with FRP which can
guarantee the performance under the high temperature environment and evaluate the effect of residual strength of BFRP to structural safety. In addition, it is also a major concern whether toxic gases are released from the FRP composites subjected to fire. To address the above problems, the tensile property of BFRP bar (8mm in diameter and 60 vol% of fibers) pultruded with a vinyl ester has been verified under the temperature up to 300°C. The results (Fig.6) show that the bar was able to maintain about 85% of its tensile strength due to the high Tg of vinyl ester (around 120°C). It is also indicated that the pultruded FRP has a better homogeneity and can achieve higher residual strength.

![Fig.6 Tensile strength of basalt FRP bars](image)

To further clarify the mechanism of tensile degradation of BFRP under elevated temperatures, the basalt fiber bundles were tested under the temperatures up to 500°C, subjected to different conditions, tension under heating and after heating. The degradation of tensile strength of basalt fibers is shown in Fig.7, which shows in general, below 200 °C the tensile strength stays constant and gradually decreases between 200 and 300 °C, and noticeably drops after 300°C, and finally reaches the minimum at 500°C. The degradation of strength under tension while subject to heating is faster than when it is under tension and the temperature has exceeded 300°C. This phenomenon shows that no damages on fibers can be caused under 200°C and the damage can be accumulated and accelerated with the elevation of the temperature after 200°C. In general, the tensile strength of basalt fibers degraded faster when they were tensioned under heating compared with those tensioned after heating. Besides the test of basalt fibers under the temperatures up to 500°C, the BFRP bars with diameters of 6 mm were also tested. The strength degradation is also shown in Fig. 7 in compassion with those of basalt fibers. The degradation trend of BFRP is similar to that of basalt fibers under elevated temperature, which indicates that the state of fibers in the FRP mainly controls the overall strength of FRP.

![Fig.7 Strength degradation of basalt fibers and BFRP bars](image)
The strength degradation of the aforementioned tested BFRP bars with 6-mm and 8-mm diameters are also compared with those of CFRP, AFRP, GFRP, and steel bar referred from [10 -11]. The results show among different FRP bars, BFRP bars exhibit superior high strength retention within 300 °C, which is similar to the performance of steel bars and CFRP, and much better than that of GFRP and AFRP bars. However, the limitation that BFRP bars almost lose their strength under the temperature of 500 °C still should be investigated thoroughly.

2.2.5 Properties under severe environment

(1) Under freeze-thaw cycles

In order to evaluate the mechanical properties of basalt FRP under severe environment (such as in North China, Northwest Territories, as well as coastal areas), the research team tested the mechanical properties of BFRP sheet under the freeze-thaw cycles [12-13], meanwhile, references [14] tested the mechanical properties of carbon fiber and glass fiber under the same conditions. For comparison three types of FRP are presented in Fig. 9. The results shows that no obvious change was found in failure mode between the exposed coupons and the controled ones. The ultimate strength of CFRP and GFRP sheets decreased continuously with the increasing cycles, while BFRP sheet decreased slightly before 100 cycles and later increased. Freeze-thaw cycles did not affect the modulus of elasticity of these three FRP sheets. The ultimate strain of CFRP and BFRP sheet fluctuated with the increasing cycles and BFRP sheet showed a higher retention rate than CFRP and GFRP sheets under high freeze-thaw cycles.

(2) Under alkali solution

BFRP applied in RC structures is usually affected by the alkali action due to its embedment inside the concrete. To evaluate the alkali effect on the BFRP reinforcement, accelerated aging tests are conducted to verify the mechanical degradation. The test specimens included BFRP bars (a diameter of 6mm) with vinyl ester resin which is under 55°C alkali solution with a PH value of 13. The experimental results are shown in
Fig. 10, which are also compared with the alkali resistance performance of E-glass and T-glass FRP rods [15-17].

Fig. 10 Degradation of BFRP, E-glass and T-glass FRP

Results show that the initial strength degradation of basalt/vinyl ester is similar to that of E-glass/polyester and T-glass/riproxy, but faster than that of the E-glass/vinylester due to the influence of the diameter of the bar. It is also shown that after initial degradation, the strength degradation rate of balsalt/vinylester is obviously slower than the other FRP rods. In this regards, it is concluded that BFRP should have stronger resistance compared to E-/T-glass FRP. But more experiments of BFRP should be conducted to develop prediction model.

(3) Properties under salt solution

The corrosion due to salt is usually occurred under coastal environment which is directly affecting the FRP reinforcement such as cables. Considering the actual load condition of those FRP reinforcements, the prestress load is considered in the evaluation of their behavior under salt solution. The 6 mm diameter BFRP bars with vinyl ester under the room temperature were tested.

The degradation of BFRP with regard to the aging days subjected to different levels of stress ratios is shown in Fig. 11(a). Overall, the retention of tensile strength of BFRP tendons remains high (over 90% of tensile strength) independent of the curing days and the stress levels. This demonstrates BFRP tendons can resist saline corrosion in different applications such as stay cable or external prestress cables. The apparent drop of strength can be found within the initial thirty days, after which the degradation rate is lowered. It is also apparent that with the higher level of stress, the degradation of tensile strength is larger, whereas the amplitude of strength degradation between the tendons subjected to pres=0 and pres=0.3fu is larger than that between the tendons under pres=0.3fu and pres=0.6fu. This phenomenon indicates that, on one hand, the applied stress aggravates the degradation of BFRP tendons. This can be interpreted that the stress in FRP contributes to the propagation of micro-cracks in the matrix, which make corrosive ions easier to penetrate into the matrix and damage the interface between the fibers and the matrix. On the other hand, the contribution of high stress to degrade the tensile strength is nonlinear, which means the propagation of micro cracks is more sensitive to the initial stress rather than the higher stress.
Although the differences of modulus variations are identified as shown in Fig. 11(b), it is still difficult to figure out a distinct trend of variation of modulus due to the overall small amplitudes (less than 3.5%). This small amplitude of variation indicates the salt solution has slight effect on the degradation of modulus and indirectly demonstrates that the corrosive elements mainly affect on the matrix and the interface between the matrix and the fibers.

2.2.6 Typical engineering applications for BFRP

Above BFRP products have been used in various infrastructures and gradually prove their advantages in integrated high performance applications. Some regular and typical applications in civil infrastructures are introduced as follows.

(1) Chopped basalt fiber-reinforced asphalt pavement[18]

With the increasing development of road transportation in China, the traffic volume and axis load continues to increase. The requirements for the high quality and longer service life of the asphalt pavement are also becoming more strict. As more new materials are used in the asphalt pavement technology, adding fiber in the asphalt mixture for enhancing the performance of asphalt mixture becomes 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 compared with the other fibers because of its desirable mechanical properties and high temperature performance.

Fig. 12 and Fig. 13 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.
Recently, Hangjinqu Highway K143 +512 ~ K144 +141 section incorporated 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 have improved, for instance there is no presence of oil on the surface and no loose phenomenon. Based on the core taken from the onsite condition, the compaction degree are up to 99%, and the water permeability coefficient and anti-slip values can all meet the specification requirements. 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 This results 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. 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 participated in the on-site condition test from 2008 as show in Fig.14.

(3) BFRP bars for non-magnetic structure

The elastic modulus of the BFRP bar is relatively low (currently about 55GPa) compared to conventional steel, 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. For example, in 2007 in
order to meet the seismostation’s non-magnetic requirements, Lanzhou Seismological Bureau uses BFRP bars instead of steel bars in the construction of seismostation (Fig.15). Southeast University developed the bending manufacture technology in order to solve the reinforcement bending and stirrup making problem. The seismostation works well at present.

In May 2008 the Southeast University, Zhejiang GBF Basalt Fiber Co., Ltd. and Zhang Shi Shijiazhuang highway management jointly develop a continuous reinforcement construction technology using BFRP reinforcement to enhance the road, taking north and south ends of the Xingtang Bridge for the trial (Fig.16). This continuous reinforcement construction technology achieve a truly non-welded connection, reducing the shrinkage cracks of the concrete blocks, it also resolve the corrosion effect of the de-icing salt compared to the steel reinforcement, which improve the quality and durability of highways and reduce highway costs, shorten construction time.

(4) Structural seismic strengthening

Because the priority concern of structural seismic strengthening is ductility rather than strength and stiffness, basalt fiber sheet have a unique advantage comparing to the carbon fiber sheet in this area. The research team performed comparison test between BFRP and CFRP wrapped column [22]. Fig. 17 shows the testing hysteresis curves of the columns with no strengthening, with 2.5 layers of wrapped CFRP, with 4.5 layers of wrapped CFRP and with basalt fiber bundle circle around the columns, which 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 compared to the others, and the basalt fiber bundle can also change the failure mode of the column. Under the similar lateral restraint stiffness, the continuous basalt fiber sheets strengthened columns can achieve the same or higher strength, energy dissipation and ductility but lower price than CFRP strengthened columns. Thus, the BFRP is more suitable for structural strengthening with higher seismic performance.
(5) Underwater strengthening with BFRP grids

Offshore infrastructures encounter severe natural surroundings like chloride attack, tsunami, tidal waves, earthquake, etc. Reinforcement concrete and steel structures are vulnerable in severe environments, which may damage their durability and load carrying capacity. Also, the cost for regular inspection and repair is tremendous. Considering the particularity of strengthening underwater structures, bonding and curing are two significant concerns. It is usually difficult for FRP sheets to bond evenly on the surface of underwater concrete elements due to the influence of water. For this sake, the application of FRP sheet strengthening underwater structures is restricted. Therefore, the special BFRP grids have been exploited to solve this problem. The procedure of strengthening underwater column with BFRP grids is shown in Fig. 18. The first step is to treat the concrete pier’s surface, and then paint it with an underwater type of epoxy resin to a thickness of about 2 mm. After, BFRP grids are bonded to the surface by pressing them into the adhesive layer. In the last step, the epoxy is re-painted to a total of 5 mm thick.
The sufficient bonding capacity between BFRP grid and concrete surface has been obtained through single-lap shear and three-point loading tests, whereas the same magnitude of capacity has been obtained with BFRP grids, which only have 70% fibers compared with BFRP sheets.

(6) BFRP sandwich structures

The structures facing impact and explosion loads are becoming more prominent. It is needed to develop new materials and new structures with integrated high performance. From previous experience, it is not recommended 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 an upper panel, a core material and a 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 proposed basalt fiber reinforced polymer-lightweight aerated concrete (BFRP-ALC) sandwich structure (Fig. 19). This new type of sandwich structures can be widely not only used in the fields of 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 and the results are satisfactory.

Fig.19 BFRP sandwich structure

3. Advancement of BFRP composites

Due to the structural multi-requirements including capacity, stiffness, ductility, stability and economy, one kind of FRP usually cannot satisfy above needs due to their relatively simplex advantage. For instance, BFRP has high tensile strength but its relatively low elastic modulus usually causes structural stiffness deficiency such as stay cables in cable-stayed bridge. Another example is simply use BFRP in RC structure, the ductility and recoverability are difficult to control due to its linearity of stress-strain relationship. Focusing on above limitations, a hybrid design concept was adopted and developed for achieving integrated high-performance basalt fiber based FRP composites.

3.1 Design and advancement of basic mechanical properties

Three types of hybridization are adopted in the study to meet different structural requirements, as shown in Fig.20(a). It shows an idealized stress-strain relationship of hybrid FRP consisted of three types of fibers, high modulus, high strength and high ductility. High modulus fibers are designed to ensure the enhancement of initial stiffness. The mixture of high modulus and high strength fibers presents a certain strain hardening behavior until the rupture of the high strength fibers, which may be used to control the deformation of structures with a good recoverability. In addition, the ductility can be guaranteed by mixing with ductility fibers in certain proportions. The above hybrid design concept was also proven by experiments as shown in Fig.20(b). Based on above hybrid concept of hybrid fibers, the other two hybrid
methods were developed \(^6,25\), which hybridizes fibers with conventional structural materials including steel wires and steel bars. The hybrid basalt and steel wires FRP can achieve initial high modulus, secondary stiffness and relatively ductility meanwhile the self-weight will not increase obviously which can still benefit application in long-span structures (Fig.21(a)). Fig.21(b) shows a hybridization between fibers and steel bar, which is majorly applied for RC structures. By this method, a stable secondary stiffness can be realized which guarantees structural ductility and benefit structural damage controllability and recoverability under moderate to large earthquake.

![Fig. 20 Hybridization of three types of fibers](image)

(a) Concept design  
(b) Experimental results

Fig. 20 Hybridization of three types of fibers

![Fig.21 Hybridization of basalt fibers with conventional steel](image)

(a)  
(b)

Fig.21 Hybridization of basalt fibers with conventional steel

### 3.2 Enhancement of fatigue behavior

To further investigate the advantages of hybrid FRP aside from their contribution to the basic mechanical properties, the fatigue behavior of hybrid basalt and carbon, carbon and glass FRP sheets were tested. It can be seen from Fig. 22 that the fatigue strength of BFRP sheet is significantly improved through hybridizing basalt and carbon fibers with the volumetric ratio of 1: 1. After hybridization, the hybrid B/CFRP composites can maintain the 2 million cycles without fracture (Fig. 22) at 70% of the maximum stress (amplitude R=0.1), which is approaching the fatigue strength of CFRP sheets (77%). This result indicates the fatigue performance of BFRP can be designed through hybridization according to the structural requirement and the enhancement of fatigue strength is effective. However, the hybrid G/CFRP sheets show even lower fatigue strength than GFRP sheets, which is mainly caused by the week bonding between glass...
fibers and carbon fibers [9].

3.3 Enhancement of tensile properties under elevated temperatures

To clarify the hybrid effect on FRP under elevated temperatures, the hybridization of carbon and basalt FRP, and carbon and E-glass FRP was tested under the temperatures up to 200°C. The tests results show that hybridization contributes the reduction of dispersion of tensile strength of CFRP at high temperatures, which means the strength become more stable and can be used more sufficiently in the design (Fig. 23) [26].

It is shown that the thermal properties of the resin greatly affect the properties of FRP under elevated temperatures. Thus, to enhance the properties of FRP under elevated temperatures, it should be ensured that the matrix of FRP have good high-temperature performance. The research team studied the high-temperature performance of FRP up to 500°C with different resins, phenolic-based (TG-1009) and
epoxy resin. The results shown in Fig.24 indicate that although the tensile strength of FRP with TG-1009 resin is not as high as the FRP with epoxy resin at room temperature, the FRP with TG-1009 resin can maintain the room-temperature tensile strength up to 300°C which is 35% higher than the FRP with epoxy resin.

Based on above studies, the models for predicting high temperature properties of FRP were proposed as follows, which can represent the strength degradation of FRP below the temperature of decomposition [27].

\[
\sigma_r = \frac{1}{2} \left( \sigma_0 - \sigma_f \right) \tanh \left( -\frac{1}{\Delta T/2} \left( T - (T_g + \Delta T/2) \right) \right) + \frac{1}{2} \left( \sigma_0 + \sigma_f \right)
\]

\(\sigma_r\) is the residual strength, \(\sigma_0\) is the strength at room temperature, \(\Delta T\) is the temperature variation of the glass transition region of the polymer matrix, \(T_g\) is the glass transition temperature, and \(T\) represents the temperature.

Aside from evaluation and prediction of FRP under elevated temperatures, the design theory based on the residual strength of FRP is still under developing. The FRP performance under high temperatures and under the fire should be further investigated and accumulated to guide the application in structures.

3.4 Advancement of mechanical properties of BFRP under severe environment

(1) freeze-thaw cycles

As can be seen from Fig. 25, hybrid FRP sheets show a better freeze-thaw cycling resistant capacity than homogeneous FRP sheet. There were no significant decreases in ultimate strength and modulus of elasticity within 200 cycles. About 10% reduction was found in ultimate strain of 50 and 100 cycles exposed 1C2B specimens, but there were nearly no decreases in 150 and 200 cycles exposed specimens. 1C1B performed better than 1C2B FRP sheets under freeze-thaw cycling condition. Overall, there are higher COV values of exposed specimens than the control ones. This may due to the non-uniform impact on the coupons during freeze-thaw cycling test. Hybrid FRP sheets have lower COV than the corresponding homogeneous CFRP and BFRP sheets after exposure, which indicates that the hybrid of fibers could contribute to the stability of mechanical properties of FRP sheets after being exposed to freeze-thaw cycling.

(2) Under salt solution with prestressing
Aside from the BFRP tendons under salt solution, the two types of hybrid FRP tendons as well as CFRP tendons were tested to identify hybrid effect and the potential enhancement in comparison to BFRP. The test results of the tensile strength retention with respect to stress level after 120 days aging are shown in Fig. 26. It apparently shows that the applied stress accelerated the strength degradation of different kinds of FRP tendons, among which CFRP tendons exhibit the strongest resistance to salt corrosion, followed by B/CFRP, BFRP, whereas the degradation of B/SFRP is largest. The strength degradation of B/CFRP is quite similar to that of CFRP and smaller than that of BFRP, for the specimens without applied stress, which may be contributed by the positive hybrid effect of basalt and carbon fibers. However it also shows a similar drop of strength to BFRP, for the specimens with applied stress, in which no positive hybrid effect on lowering degradation rate can be found. For B/SFRP tendons, much larger degradation of strength can be observed in comparison to CFRP, BFRP and B/CFRP, which indicates the steel wires corroded in B/SFRP tendons perform an important role in strength degradation. However, no clear relationship between the CV of tensile strength with respect to applied stress can be observed as shown in Fig. 27.

4. Innovative application technologies for structures with BFRP

Based on above fundamental studies, the BFRP and the relevant hybrid FRP composites were investigated to realize safety and sustainability in various civil and transportation engineering. The following will summarize the major applications.

4.1 BFRP smart bar for structural health monitoring

The self-monitoring BFRP smart bar is shown in Fig. 28. It is constructed by putting the distributed optic sensors in the manufacture process of the BFRP bars which make the bar be capable of self-monitoring, self-diagnostic. The stability and durability and its mechanic property of this smart bar 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 transportation facilities \(^{[28-30]}\). The smart bars can be embedded in concrete beams and they can monitor the structural state during the entire serving life (static load tests). Fig. 29 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 Fig. 30, 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 (Fig. 31). It provides a new thought of how to solve the monitoring hardness under complex geological environment.
4.2 BFRP and hybrid FRP cables for long-span bridges\[31-34\]

To meet the world wide need for long-span bridges over the bay or strait 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 materials. The research team proposed the use of BFRP and hybrid FRP cables as a replacement of the traditional steel cables as to achieve the high-performance and balance the economic issue. Traditional steel wire (strand) will affect the overall performance of bridge because of its shortcomings like heavy weight and is prone to corrosion when in the span of 1000 meters. Some scholars proposed that using carbon FRP cable can solve above problems, but the large-scale application is limited because of its high price. Also, the carbon FRP cable is more sensitive to the wind effect because of its high strength and low density. Based on this, the research team put forward a method of using basalt-carbon fiber composite cable to achieve the high performance. The research results indicate that: (1) the hybrid basalt-carbon FRP 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% (Fig. 32,33); (2) the aerodynamic stability performance of the hybrid basalt-carbon FRP 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 sectional design based on the different attributes of two FRP inside the cable (Fig.34); (3) the self-damping cable shows lower resonance amplitude and stress amplitude under indirect excitations comparing to the CFRP cable and steel cable, which benefits the safety and long-term performance of the cable (Fig.35).

In addition, the research team has also developed a basalt fiber-steel wire FRP cable which is suitable for the bridge with a span less than 2000m span, which have a better performance-price ratio. The author also analyzed and evaluated the applicability of four types of cables in the span range from 1000m to 10000 meters including two composite cable mentioned above and pure BFRP cable and CFRP cable based on the utilization ratio of each material (Fig. 36). Meanwhile the FRP cable can also be combined with the distributed optic sensors. The design is of great importance to the real-time monitoring and real-time control of cable under traffic load and wind load (Fig.37).
4.3 Prestressed BFRP for structural strengthening

Since most of the fiber composite has low elastic modulus than steel, and the existing structures have already been under load condition before strengthening, 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, a prestressing technology of FRP sheet was proposed in order to improve the material utilization. The fiber sheet without being impregnated with the matrix has low tensile strength, so the applied prestressing cannot be effectively imposed on the structure. On the other hand, if the sheet is impregnated in the matrix and hardened, the fiber sheet is difficult to attach to the structure because of its curving surface after matrix hardened. To solve this conflict and improve the utilization efficiency of fiber sheet, the research team proposed the dry hybrid carbon-basalt fiber sheet to form a new composite sheet in order to achieve the high strength tensile of dry hybrid fiber sheet (Fig. 38). The different hybrid ratios were tested and compared and the results show that tensile strength of dry carbon fiber sheet increase from 30% to 54% of the FRP, which guarantee the implementation of high prestressing on the fiber sheet. With this method, a flexural strengthened beam with one layer of basalt fiber plus three layers of carbon fiber was tested which endures 33% of the tensile prestressing of dry fiber. The results are shown in Fig. 39. It can be seen that the prestressing play an important role in improving the strength and post-stiffness of structure.

Fig.38 Tensile strength of 2m long fiber sheets

Fig.39 L-D curves of prestressed strengthening beams

Basalt fiber sheet can achieve the pre-tension by not only hybridizing with carbon fiber sheet but also by hybrid with steel wires (B/SFRP) with a small diameter (also called piano wires), which can improve the overall stiffness and the cost will not increase much (Fig. 40). As shown in Fig. 34, the stiffness of two layers of basalt fiber sheet can be significantly improved to like three layers by hybridizing 20% of piano wires in volume. The tests on the beams prestressed strengthened with this type of basalt-steel wire sheet show that the crack load and yield load are both increased as show in Fig. 41.
An innovative strengthening method by prestressing BFRP tendons was also investigated as shown in Fig. 42, in which BFRP tendon was externally bonded on the bottom of the beam by epoxy resin. A special bond process was developed to guarantee reliable interfacial bonding as shown in Fig. 43.

The experimental results are shown in Fig. 44. In Fig. 44(a), it is shown that the beam with 25% prestressing BFRP tendons exhibits higher cracking load and much smaller crack width comparison with non-prestressing BFRP strengthened beam and control beam. Meanwhile, up to the cracking limitation (0.2mm), the 25%...
prestressing BFRP strengthened beams have double capacity than the control beam. Fig.44(b) shows the L-D curves of beams with prestressed and non-prestressed BFRP tendons, in which prestressing BFRP tendon strengthening contributes improvement of cracking load, the stiffness before steel yielding and the yielding load. Both figures also show that the experimental results fit well with the analytical results, which indicates the current prestressing method can be used for design in application.

### 4.4 Damage controllable and recoverable structures with SFCB or partially with BFRP bars

In order to realize damage controllability and recoverability of structures, the structural behavior under different load magnitudes is divided into four states as shown in Fig. 45. The first state represents the structure before yielding of reinforcement, which is corresponding to the elastic status and the status of cracking. Within this stage, structural members have no need to repair due to their elastic behavior under the earthquake. In the second state, the nonlinear behavior represents the structures under the moderate magnitude of earthquake due to the yielding of steel reinforcement. In this stage, a stable secondary stiffness of structure exhibits which benefits for the structural deformation control and rapid recovery after damage. The third state represents the deformation ability of structure after secondary stiffness, which requires sufficient deformation ability under large earthquake. In this state, the structure can be recovered by replacing partial damaged members. For the fourth state, the structure is subjected to rare extremely large earthquake and the aim is to prevent structure collapse.

![Fig.45 Schematic of damage controllable and recoverable structures](image)

Two ways are currently investigated to realize structural damage controllability and recoverability, the structure reinforced with SFCB and the structure with hybrid BFRP and steel bars as show in Fig.46.
Fig. 46 Two ways realizing structural recoverability

The hysteretic curves of the columns with SFCB and hybrid BFRP/steel are shown in Fig. 47 (a) and (b), respectively. It can be seen that compared to the regular RC column, the SFCB strengthened columns show obvious secondary stiffness and smaller residual deformation after unloading. These two characteristics are of great importance to realize the energy dissipation, damage control and post-earthquake recovery of the construction. Aside from the columns with SFCB, the columns with partial BFRP bars also show obviously the stable secondary stiffness and the less residual deformation in comparison to that of the conventional steel reinforced columns. The results further prove the proposal of the damage controllable and recoverable structures.

(a) by SFCB

(b) by hybrid BFRP and steel

Fig. 47 Hysteretic curves of columns strengthened with SFCB and partial BFRP under cyclic loading
Above application of hybrid BFRP and steel bar for damage recoverable and controlable columns can also be used for retrofitting existing RC columns, which is realized by near-surface mounted BFRP bars on the sides of the column as shown in Fig.48. The hysteretic curves also shows stable secondary stiffness and smaller residual deformation after unloading.

The current research also investigated the effect of two factors controlling the strengthening effect of columns by BFRP bars, the diameter of BFRP bars and the bonding materials, respectively. Envelope diagram of load-deformation of BFRP NSM strengthened columns is shown in Fig.?, in which three types of diameters (6mm, 10mm and12mm) and two types of bonding materials (E: epoxy putty and EP: polymer cement) are considered. The results indicate that more stable secondary stiffness and more ductile behavior of columns can be achieved by thicker BFRP bars based on the equivalent reinforcement ratio. Because the relative slippage between BFRP and RC occurs easily for thicker bars due to their small interfacial area, which allows more sufficient use of BFRP materials under the cyclic loading and fail by fracture of BFRP bar. On the contrary, the columns with thinner BFRP bars, the collaborative work between BFRP and RC column due to more reliable bonding will limit the relative slippage and lower the utilization efficiency of inner BFRP bars (pull out of BFRP bar). The results also shows that for thicker BFRP bars, the adoption of
epoxy putty can achieve high bonding capacity and ductility with the failure mode controlled by BFPP fracture as shown in Fig.49.

**Fig.49 Pull-out test of BFRP bars with different bonding materials**

### 4.5 BFRP profiles for sustainable structures

The fiber sheets are usually used for the reinforcement of the existing structures; however, the FRP profiles are more suitable for the construction of the new structure. FRP Profiles not only have fixed shape which can be used as structural formwork, but also through the use of wet-bonding techniques, it can effectively guarantee the reliable bond between FRP profiles and structure, which makes FRP profiles achieve full strength, improves the bearing capacity of the structure of guarantee ductility. Based on this, the research team has studied and developed the T-shaped basalt-carbon fiber-concrete composite beam (Fig. 50). The hybrid BFRP and CFRP on the bottom of the girder can increase the stiffness and maintain ductility and the shear reinforcement by BFRP can achieve sufficient shear strength and lower the cost. The tests results (Fig.51) show that (1) comparison of results of several bonding methods, including wet bonding, dry bonding and pre-bonded gravel, shows that each bonding method can achieve good results, in which wet-bonding approach not only can obtain good results, but also facilitate the rapid construction; (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 of CFRP, and the layers of BFRP are directly proportional to this effect. As a result, the material utilization efficiency is improved. In addition, the wet-bonding plus shear studs composite beams were also investigated as shown in Fig.52, which shows not only reliable bonding of interface between concrete and FRP can be achieved, but also superior flexural behavior under the static and cyclic loading can be realized.
5. Summary and suggestions

This paper summarizes the recent research and application of basalt fibers and the composites in the field of civil and transportation infrastructure in order to enhance the structural safety and sustainability. It is clarified that basalt fibers have excellent compatibility with matrix resin and can be hybridized with steel wires, steel bars, or other fiber materials achieving a prominent hybrid effects shown in short-and long-term mechanical properties, fatigue resistance, high temperature performance, and etc. Aside from the general structural reinforcement by BFRP composites, the basalt FRP and hybrid FRP are also able to play an important role in smart structures, long-span bridges, damage controllable and recoverable structure, light-weight and sustainable structures, and etc. Based on the above study, some recommendations on the future development are proposed as follows:

(1) Accelerating development of new basalt fibers and BFRP products

In order to be better and faster in promoting wider fields of applying basalt fiber composites, the research and development of basalt fibers and the related FRP products should be accelerated to solve current problems, bridge gaps between research and application, and lower the cost.

(2) Strengthening basic research

Currently, since the application of basalt fiber composites is in precede of basic research, in order to have a better and more scientific application, the systematic study of the short- and long-term, static, dynamic, extreme environmental properties of basalt fiber and its composites should be strengthened to establish the
corresponding theoretical model and design methods to guide the practical application.

(3) Rational use of basalt fibers and the composites

Basalt fibers and the composites have many advantages, but there are shortcomings as well. They should be developed objectively and used dialectically. Thus, a systematically comparison and combination of the advantages and weakness among BFRP and CFRP, GFRP and AFRP should be conducted seriously, through which full use of advantages and healthy development of different fiber composites in engineering can be expected.

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