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A study on the mechanical properties of aramid/basalt fiber hybrid composite for marine use

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해상용 Aramid/Basalt 섬유 Hybrid 복합 재료의 기계적 특성에 연구

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Abstract

Fibre-reinforced composite materials (FRPs) have been used successfully in marine and offshore applications for several decades in areas such as cabin modules, super yachts, work boats and leisure craft. Materials used in marine use need high specific stiffness and strength, good corrosion resistance and good design-ability. Marine composite strives to be an up-to-date compendium of materials, design and building practices in the marine composites industry - a field that is constantly changing. Designers should seek out as much technical and practical information as time permits. Aramid fiber in marine composites and maritime vessel composites helps provide an ideal balance of strength, stiffness, and lightweight properties for many marine applications. Basalt fiber has good tensile strength and elastic modulus which are better than normal fibers and it is becoming the first choice of composite reinforcement. In this paper, tensile and bending properties of aramid/basalt hybrid fiber reinforced polymer was studied by the experimental data analysis and fracture morphology observation. 6 kinds of samples with different fiber content and 6 types of samples with different ply sequence were produced together with neat AFRP and BFRP using the VaRTM process. Further studies found that adding HNT additives can improve performance to a certain extent.

KEY WORDS: Aramid/basalt hybrid composites, Mechanical properties, Lamination structure, VaRTM, HNT

1. Introduction

1.1. Research background

Composite materials have advantages such as high specific stiffness, high specific strength, good design-ability and excellent fatigue resistance and it's widely applied to space technology, arm equipment technology, energy engineering, ocean engineering, biology engineering and even civilian construction and Transportation area. Recently composite materials have a developed application in marine construction such as lining, oil tank and pipe, grille and so on, widely used in harbor, sea crossings, men-made reefs and series of marine anti-corrosive engineering because of: (1) The excellent design-ability of composites and the material can be designed according to structural requirement; (2) High specific stiffness and strength which usually better than steel and aluminum; (3) Good Fatigue resistance, conventional metal's fatigue strength are usually between 40%~50% tensile strength while some composite materials industry can achieve

70%~80% fatigue strength; (4) Good Corrosion resistance and chemical reaction-resistance, traditional material such as steel can be easy to interact with air, sea water and chemical element in sewage while most composites are outstanding anti-corrosive materials, equipment and structural components made by composite commonly have abilities to resist acid, alkali and other chemical mediums. At the same time, because of its widely expand space in application aspect, the application of composite materials in ships and marine structures is also a hot topic of many scholars at home and abroad [1,2].

Hybrid fiber reinforced polymer(HFRP) is a composite material which is formed by two or more than two kinds of fiber reinforced with a matrix, it not only has the characteristics of single fiber composite materials, but also combines the advantages of fiber respectively, some of the mechanical properties of the material are significantly improved, it can be said to be a more advanced stage in the development of composite materials [3]. Basalt fiber has good tensile strength and elastic modulus which are better than normal fibers and it is becoming the first choice of composite reinforcement [4,5]. Aramid fiber is a kind of Organic fiber with high strength and low density, and even an radiation and corrosion resistance material. It's reasonable to believe that the aramid/basalt hybrid composite can have better comprehensive mechanism properties and can be applied into marine construction area [6].

1.2. Composite materials overview

Material is the foundation of all production and human life and is the symbol of human civilization progress. With the fast development of modern science and technology, people have more needs on material's properties and abilities. In this occasion, people begin to use metals, non-metals and polymers, design those materials according to the predetermined performance and make them into new materials. In this background, the composite material came into the world.

The development of composite materials can be traced back to 1960, due to the development of high strength and high modulus glass-boron fiber, and the strong demand for aerospace industry to improve weight and performance of aircraft and spacecraft. It made the development and application of fiber reinforced composite material become a rapid developing of science and technology. Today, composite materials have been widely used in electronic information, construction, transportation, aviation and military fields.

Composite material is composed of two or more than two components of different properties; using physical or chemical methods and has new properties on the macroscopic or macro level. All kinds of materials have the synergistic effect and making the properties of composite materials are better than the original components to fulfill different demands. The matrix of composite have both metals and non-metals. Typical engineered composite materials include: mortars, concrete, reinforced plastics, ceramic composites and so on. Composite materials are generally used for buildings, bridges, and structures such as boat hulls, swimming pool panels, race car bodies, the most advanced examples perform routinely on spacecraft and aircraft in demanding environments [7].

Hybrid fiber reinforced polymer(HFRP) is a composite material which is formed by two or more than two kinds of fiber reinforced with a matrix and research shows that HFRP can have comprehensive effect on its mechanical properties, this effect is not only associate with components and properties of each materials but also relative to the hybrid mode, stress type, interface conditions and energy response. Hybrid fiber can improve the impact strength, fatigue resistance and anti-corrosion property, increase the design-ability and bring series of excellent mechanical properties. Nowadays HFRPs are wildly used in aerospace, aircraft, marine construction, automotive and medical treatment applications. In marine construction area, by rationally hybrid the different type of fibers, can give the HFRP good mechanical properties in both strength, elasticity and ductility. Additionally, during the crack process of HFRP, the stress of FRP can be gradual release, slow down or even prevent the interfacial bonding damage [8].

1.3. Hybrid effect

Hybrid composites synthesize the excellent mechanical properties of every single component, the mechanical properties relate to the composition material. In some conditions, some performance will meet the mixed rule, some performance may occur positive (high) negative (low) deviation. Usually, this phenomenon that deviates from the mixed rule was known as the hybrid effect, it is a kind of special physical phenomenon of the interaction of the component materials and the resin matrix. Its mechanical behavior generally conforms to the basic laws of mechanics. The researchers propose that the hybrid effect coefficient (*Re*) can be used to measure the hybrid effect of hybrid composites. The *Re* varies with the stress state and can be expressed as:

$$R_e = (\epsilon_{HY} - \epsilon_{LE})/\epsilon_{LE} \quad (1\text{-}1)$$

Where: ε_{HY}-Breaking elongation of hybrid composite, ε_{LB}-Breaking elongation of lower elongate fiber reinforced composite; when the $R_e > 0$, it's positive hybrid effect while when $R_e < 0$, it's negative hybrid effect [9].

As for the basalt/aramid hybrid fiber composite, the mixing law can be expressed as follow:

$$E_h = v_f(E_a v_a + E_b v_b) + (1 - v_f)E_m \quad (1\text{-}2)$$

Where: v_f-Total volume content of fibers; v_a-Relative volume content of aramid fiber; v_g-Relative volume content of basalt fiber; E_h-Elasticity modulus of hybrid composites; E_c-Elasticity modulus of AFRP; E_b-Elasticity modulus of BFRP; E_m-Elasticity modulus of resin matrix.

The hybrid effect is related to many factors, but there is still no unified theory to explain its formation. The certain thing is that the composition materials, the mixing ratio, the hybrid structure, the interface and other factors affect the hybrid effect. The schematic curve of hybrid effect was shown in Fig. 1.

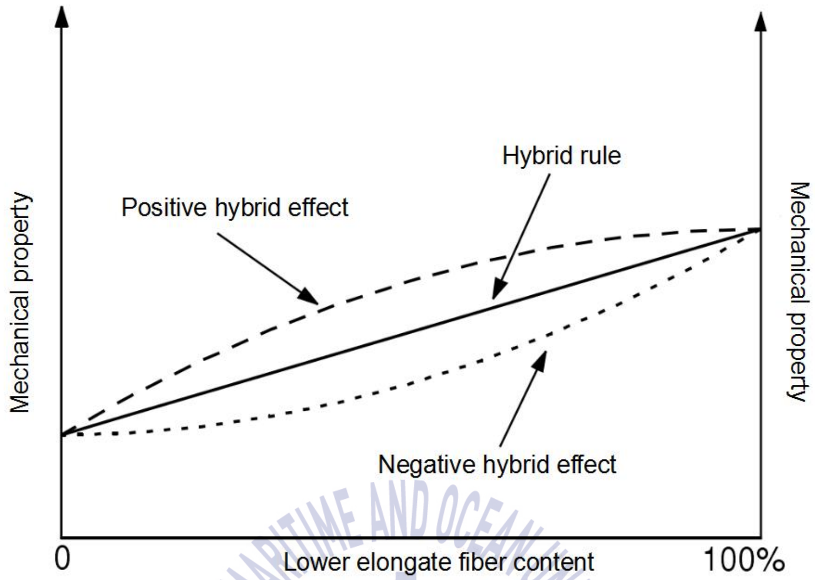


Fig. 1 Schematic curve of hybrid effect [Xu Huanhuan, 2015. *Study on Tensile Properties of Glass/Carbon Fiber Reinforced Plastics Hybrid Composites*. Master's degree. Nanjing: Nanjing University of Aeronautics and Astronautics]

1.4. Properties of aramid and basalt fiber

The raw material of basalt fiber is taken from the pure natural volcanic rock. Because of its sample raw material that can be obtained in nature and has no pollution emissions during preparation procedure, the basalt fiber became an innovative material in recent years.

The main constituents of basalt fiber are SiO_2 and Al_2O_3, with a little CaO, MgO, Fe_2O_3, FeO, TiO_2, K_2O, Na_2O and impurities. The biggest constituent in basalt fiber is SiO_2, over 50 wt%, which gives the basalt fiber excellent mechanical properties and chemical stability. The content of Al_2O_3 is 14.6%-18.3% and it further improves the chemical stability together with CaO, MgO [10].

Basalt fiber has good tensile strength and elastic modulus which are better than normal fibers and it is becoming the first choice of composite reinforcement. As a kind of new and advanced properties fiber, continuous basalt fiber has not only good mechanical properties but also the advantage in the adiabaticity, corrosion resistance and insulation. In addition, this kind of fiber has a good performance-price ratio, so it receives much concern in material field.

Table 1 Mechanical properties of carbon, basalt and aramid fiber

	Basalt fiber	Carbon fiber	Aramid fiber
Tensile strength/ (MPa)	3000-4840	2500-6000	2900-3400
Elastic modulus/ (GPa)	79.3-93.1	230-600	70-140
Elongation at break/ (%)	3.1-3.2	1.5-2.0	2.8-3.6

Aramid fiber is the generic name for any aromatic polyamide fiber. Aramid fiber is a kind of organic fiber with high strength and low density, made by Stephanie Kwolek at DuPont company in 1965 and has the registered trademark as Kevlar. The main type of aramid fiber are Kevlar-29, Kevlar-49, Kevlar HT and so on.

In the high-performance fibers used in composite materials, compare with the glass fiber and carbon fiber, aramid fiber has lower density and higher specific tensile strength. Aramid fiber also is the radiation resistant material and can resist corrosion, the strength loss ratio always below 10% in general acid-base strength. Table. 1 shows the mechanical properties of aramid fiber, basalt fiber and carbon fiber.

According to the above analysis and the advantage of basalt fiber and aramid fiber, it is expected to manufacture good comprehensive hybrid composites by mean of the design of hybrid structure.

2. Experiment and analysis method

2.1. Fabrication

In the experiment, woven fabric with plain weaving at 0° and 90° aramid fiber (HF-200) and basalt fiber (HB-200), which produced by GM COMPOSITE CO. Ltd (Korea), are used as the reinforcement and epoxy resin (KFR-120) are used as the matrix and in this experiment, 28 wt% hardener (KFH-141) was mixed with resin to form the matrix. The specification of reinforcement and matrix are shown in Table. 2 and Table. 3. 6 samples with different aramid/basalt fiber ply number are made to find the relation of mechanical properties with different fiber ratio. In this situation, samples all have laminates of 14 sheets and changes with aramid/basalt ply number: 0/14, 2/12, 4/10, 6/8, 8/6, 10/4, 12/2, 14/0. All basalt plies are in the middle of the sample and the aramid plies are put on the both sides of basalt ply averagely. 6 samples with different ply sequence are also produced, the total ply number is 14 sheets invariably and 7 aramid sheets 7 basalt sheets are used in every sample. Every stacking sequence was considered to have different aramid/basalt interface number and be maximum approximately symmetrical [11-15]. The details of ply sequence and laminate codes are shown in Table. 4.

Table 2 Specification of aramid and basalt plain woven fabric

	Aramid (HF-200)	Basalt (HB-200)
Fabric weight (g/m^2)	165	200±16
Warp construction (count/in)	13	7.5
Fill construction (count/in)	13	7.5
Fab thickness (mm)	0.18±0.025	0.18±0.025

Table 3 Properties of epoxy resin (KFR-120)

Property	Detail
Density (g/m^3)	1.0~1.2
Tensile strength (MPa)	70~80
Elastic modulus (GPa)	3.1~3.3
Elongation at break (%)	7.9~8.1

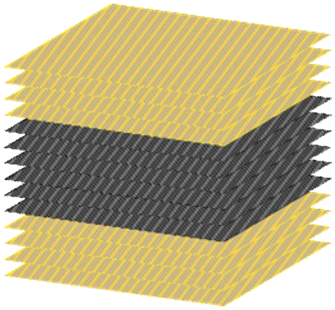


Fig. 2 The sketch of the sample with number of layers aramid/basalt = 8/6

Table 4. List of the prepared laminates with stacking sequence

Laminate code	Number of laminate	Laminating structure
AFRP	14	$[A]_{20}$
BFRP	14	$[B]_{20}$
A2B12	2(A)+12(B)	ABBBBBBBBBBBBA
A4B10	4(A)+10(B)	AABBBBBBBBBBAA
A6B8	6(A)+8(B)	AAABBBBBBBBAAA
A8B6	8(A)+6(B)	AAAABBBBBBAAAA
A10B4	10(A)+4(B)	AAAAABBBBAAAAA
A12B2	12(A)+2(B)	AAAAAABBAAAAAA
A	7(A)+7(B)	ABABABABABABAB
B	7(A)+7(B)	AABBAABBAABBAB
C	7(A)+7(B)	AAABBBBAAAABBB
D	7(A)+7(B)	AAABBBBBBBAAAA
E	7(A)+7(B)	BBBAAAAAAABBBB
F	7(A)+7(B)	AAAAAAABBBBBBB

A=aramid fabric, B=basalt fabric

After all tests, five more samples with laminate code A6B8 that added halloysite nanotube(HNT) are made to investigate the influence of bending properties. Halloysite is a clayey mineral [$Al_2Si_2O_5(OH)_4 \cdot E_2H_2O$], consisting of tubular particles with multi-layered wall structure and mainly used as a sorbent helping in the deactivation of hazardous materials after their uncontrolled leakage as well as a filler in the polymer materials and it's reasonable resumption that usage of cost-efficient HNT can help to reduce the delamination and to enhance the inter-laminar strength in the fracture test. The HNT particles was dispersed in the base material under the same ultrasonic dispersion conditions and then molded. The reason for using ultrasonic phase separation device is intended to combine the characteristics of the phenomenon of cavitation ultrasonic waves in the composite material. The dispersion of the nanoparticles was dispersed by the weight of the epoxy resin. The content of HNT was limited to 0, 0.5, 1, 2, 3, 5 wt%. This is to take into account the cohesion of HNT and to understand the range of cohesion of HNT in a matrix with viscosity and its phenomenon.

2.2.

All samples are manufactured by VaRTM. Vacuum-assisted resin transfer molding

(VaRTM) is a composite assembly technique in which a polymer resin is injected into a mold containing woven fabrics with different stackings as reinforcement of composite. It was performed in vacuum by utilizing the differential pressure between the atmosphere and a vacuum. After resin injection, the molded object was cured in an oven at 80 ℃ for more than 2 h. Compared with traditional resin transfer molding (RTM), VaRTM provides a significant savings in tooling cost as it requires only a one-piece mold, and a vacuum bag is used to close the mold. VaRTM is regarded as the most cost-effective manufacturing method. In this experiment, the aramid and basalt woven fabrics with a dimension of 300mm × 600mm were stacked on a mold made of alloy plate and then, release film and media film are put upon the fiber laminates. Two springs are put on the both side of laminates. Finally, all staffs are covered by a vacuum bagging film using a sealant tape. Then, the epoxy resin mix with hardener was injected into the mold by using a vacuum pump, waiting until all fiber laminates were penetrated by resin. finally gripping the resin inlet and outlet to keep the vacuum atmosphere. Afterward, the curing process of composites was done in an oven more than 2 h at a temperature of 110 ℃. In this experiment, fiber volume fraction can be calculated by the equation:

$$V_f = \frac{v_f{'}}{v} \times 100\% = \frac{m_f/\rho}{v} \times 100\% \qquad (2\text{-}1)$$

In this equation, V_f is the fiber volume fraction (%); v_f is the fiber volume (%); v is sample volume (cm^3); m_f is fiber weight and ρ is fiber density [16-20].

Fig. 3 Schematic of VaRTM setup

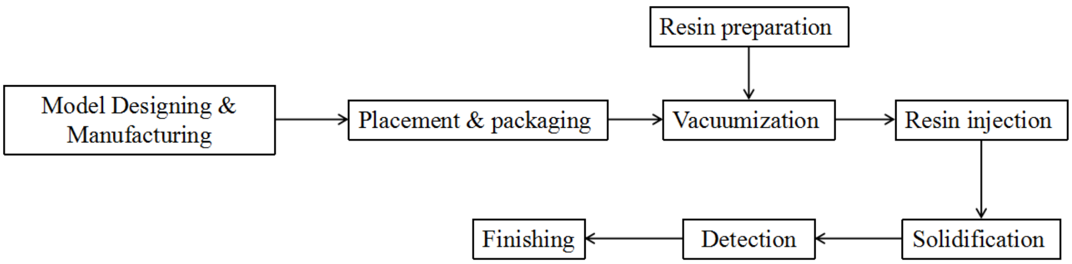


Fig. 4 Technological process of VaRTM

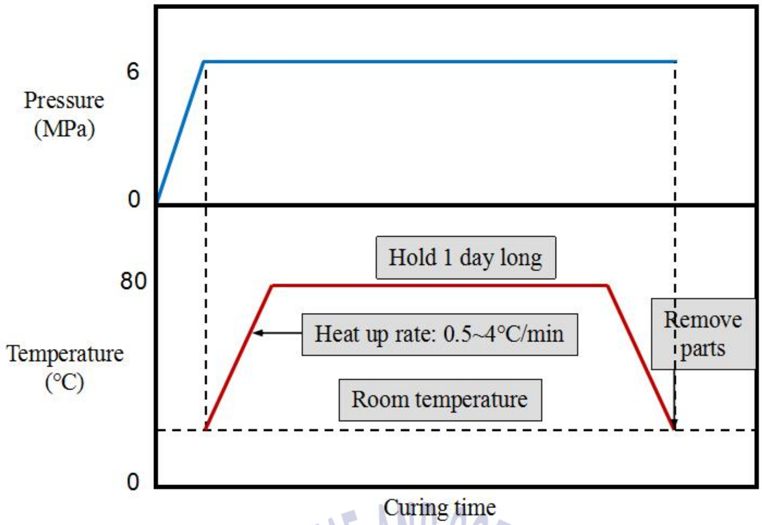


Fig. 5 Curing conditions for specimen preparation

2.3. Mechanism property tests

For every sample with different ply sequence, two test methods: tensile test and bending test were conducted to determine the comprehensive mechanism properties. Every test method, specimen configuration and computation equation was followed by ASTM which stands for American Society for Testing and Materials. The specimens were all cut by CNC cutting machine and universal testing machine (KDMT-156) was used to test the specimens. 7 specimens were tested for each configuration, and their average values are reported in this paper.

Tensile test was conducted according to ASTM D3039 (Tensile Properties of Polymer Matrix Composite Materials) at room temperature with 2 mm/min cross-head speed. The rectangular specimen configuration is 20mm × 200mm with a thickness of 3mm. Tensile stress and tensile strength are calculated by:

$$F^{tu} = P^{max} / A \tag{2-2}$$

$$\sigma_i = P_i / A \tag{2-3}$$

Where F^{tu} is the ultimate tensile stress, P^{max} is the maximum load before failure, σ_i is tensile stress of No. i data point, P_i is the tensile load of No. i data point and A is the mean cross-sectional area.

Bending test was conducted according to ASTM D790 (Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials) with 1 mm/min cross-head speed. The rectangular specimen configuration is 12.7 mm × 80 mm with a thickness of about 3 mm. The span-to-thickness ratio is 16(±1) : 1.

In the bending process, the stress of the crack tip is mainly shear type. According to the theory of material mechanics, neutral layer exists in the specimen. When the specimen become deformation after loading, the neutral layer rotates a few angle and remaining the plane. The fibers on the upper layers of the neutral plane is compressed while the fiber on the lower layers is stretched. The specimen can be regarded as a beam in 3 point bending test and during the test, the uppermost plane has the maximum surface compressive stress and the bottom plane has the maximum bending moment and failure occurs here. The maximum tensile stress on the surface is obtained by the rectangular section beam:

$$\sigma_{max} = \frac{M}{Z} \tag{2-4}$$

The maximum shear stress is :

$$W = \frac{bd^2}{6} \tag{2-5}$$

$$\tau_{max} = \frac{1.5P}{bd} \tag{2-6}$$

$$M_{max} = \frac{Pl}{4} \tag{2-7}$$

Flexural strength and flexural modulus were calculated by following equations:

$$\sigma_f = 3PL/2bd^2 \tag{2-8}$$

$$E_f = \frac{\Delta F L^3}{4bd^3 \Delta f} \quad (2\text{-}9)$$

Where W is Section coefficient (cm^3), M is the bending moment (N·m) σ_f is the flexural strength (MPa), E_f is the flexural modulus. P is the maximum load (N), L is the support span (mm), b and d are the width and thickness of the samples (mm). ΔF is load increment of straight line segments on the load-strain curve and Δf is the incremental deflection at the mid-span.

(a) (b)

Fig. 6 Photograph of tensile test and bending test

3. Results and discussion

3.1. Effects of aramid/basalt HFRP fiber content on mechanism properties

3.1.1. Tensile behavior

The tensile properties of aramid/basalt HFRP are different with the fiber types, the relative volume content of fibers and the stacking sequence. For specimen with different aramid/basalt ply number, the tensile strength of aramid fiber composite are much better than basalt fiber composite and the AFRP has a longer elongation at break than BFRP. In the hybrid situation, aramid/basalt hybrid composites have the tensile strength between the AFRP and BFRP. Between the range of 0%~30% aramid fiber relative weight content, the tensile strength increase with the aramid content, then the tensile strength goes down in 30~50%, after the 50% point, tensile strength starts to increase again. The tensile strength has the most obvious increasement during 60%~80% aramid fiber content. The elastic modulus of aramid/basalt HFRP are all between the AFRP and BFRP and all specimens performed linear elastic behavior before failure. The tensile strength corresponding to relative aramid fiber content was shown in Fig. 7 and the loading-displacement curve was shown in Fig. 8.

Table 5 Tensile strength corresponding to relative aramid fiber content

Laminate code	Aramid fiber content/ (wt%)	Tensile strength/ (MPa)
BFRP	0	426
A2B12	12	430
A4B10	25	443
A6B8	38	439
A8B6	52	441
A10B4	67	466
A12B2	83	499
AFRP	100	503

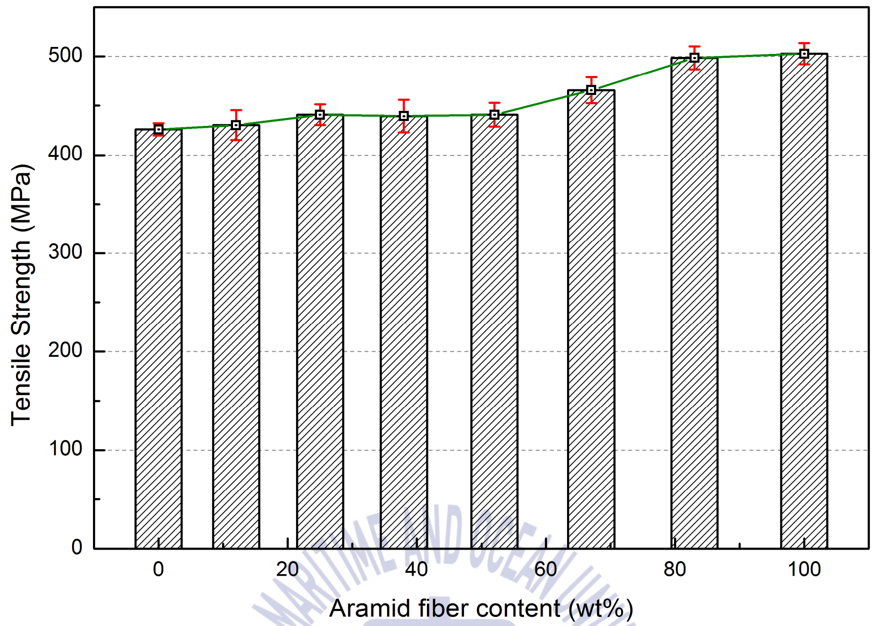


Fig. 7 Effect of aramid content on tensile strength

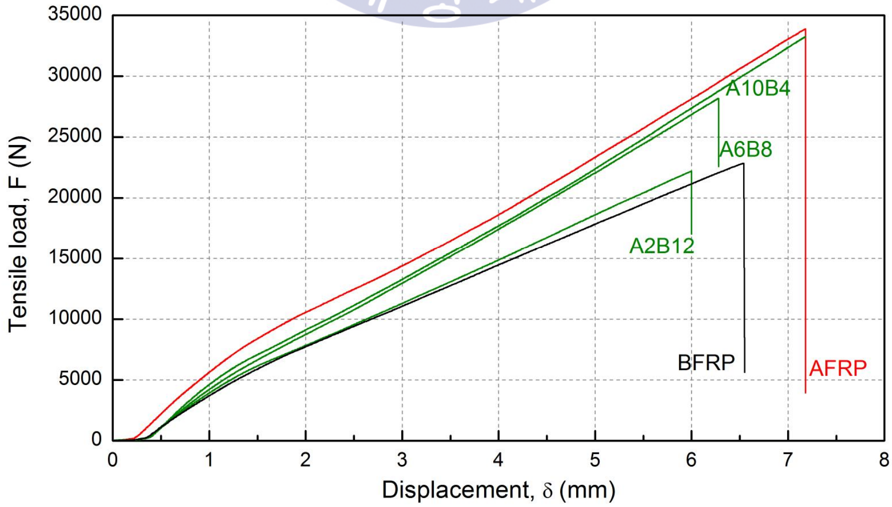


Fig. 8 Effect of aramid content on tensile load-displacement curve

3.1.2. Flexural behavior

Fig. 9 shows the bending strength corresponding to relative aramid fiber content and Fig. 10 shows the load-displacement curves of aramid/basalt fiber hybrid composite under flexural loading. The AFRP and BFRP comprising mono-materials had bending strengths of approximately 240 MPa and 300 MPa, respectively. The maximum bending strength was observed at 70 aramid fiber relative weight content which is 420 MPa and all aramid/basalt hybrid fiber reinforced composites have the better bending stress compare to both AFRP and BFRP. The pattern of load-displacement curves are different and this infers the difference of flexural behavior. The BFRP firstly has the linear displacement increasement together with bending loading, then it performed loading decreasing after the linear behavior and subsequent failure. AFRP has no linear behavior and the increasement of bending load occurred the initial loading moment and the bending loading flattened out with the displacement increase. After AFRP reached the maximum loading point, the loading drop down and occurred subsequent failure. The AFRP can endure a severe deformation and without failure. In the hybrid situation, in spite of the fiber content, all specimens have approximate linear elastic behavior after bending loading started and the more basalt fiber content the specimens have, the more loading-displacement curves are approach to linearity. For the specimens having high aramid fiber content have no subsequent failure but break as soon as they reached the maximum point. All aramid/basalt HFRPs have the better maximum bending loading and better bending stress compare to AFRP and BFRP, the maximum loading exceeded 650 N and it's nearly 30% better than AFRP and 60% better than BFRP.

Compare with the tensile behavior and bending behavior, it's obvious that in different stage of aramid fiber content the composites have different tensile and bending behavior. Between 0~25% aramid fiber content, the tensile strength and bending strength all increase together with aramid content, especially the bending stress increase sharply. During 25~50% percent, tensile strength remain unchangedand the bending stress maintains a steady trend. in this stage, the increasement of aramid fiber has no obvious significance and even can lead a worse tensile stress. During 50%~70% aramid fiber content, the tensile strength and bending strength begin to rise again, the tensile strength has a rapid growth and the bending strength reaches its maximum value 424 MPa at 70% aramid fiber content. after 70% aramid fiber content, the tensile strength keeps its sharp increasement while the bending strength drops quickly.

Table 6 Bending strength corresponding to relative aramid fiber content

Laminate code	Aramid fiber content/ (wt%)	Bending strength/ (MPa)
AFRP	0	235
A2B12	12	294
A4B10	25	374
A6B8	38	382
A8B6	52	398
A10B4	67	424
A12B2	83	380
BFRP	100	295

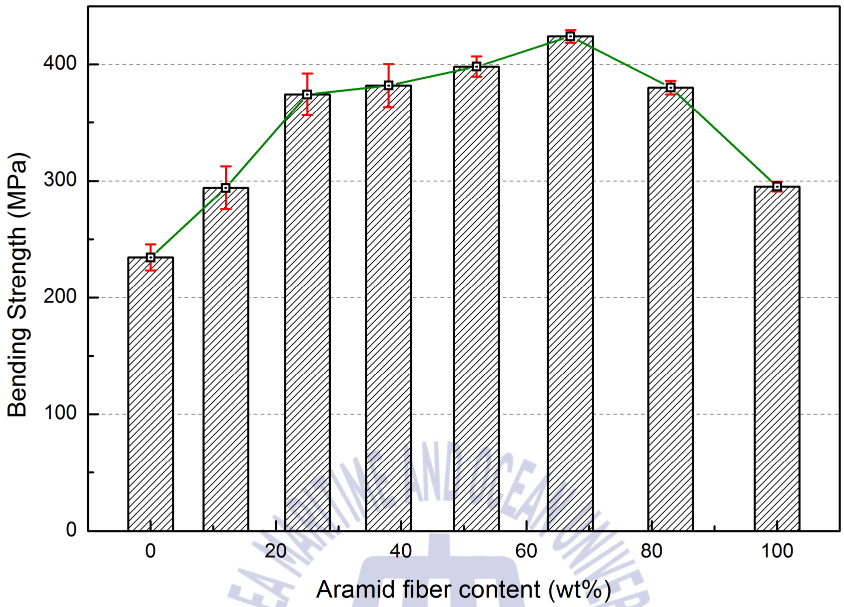


Fig. 9 Effect of aramid content on bending strength

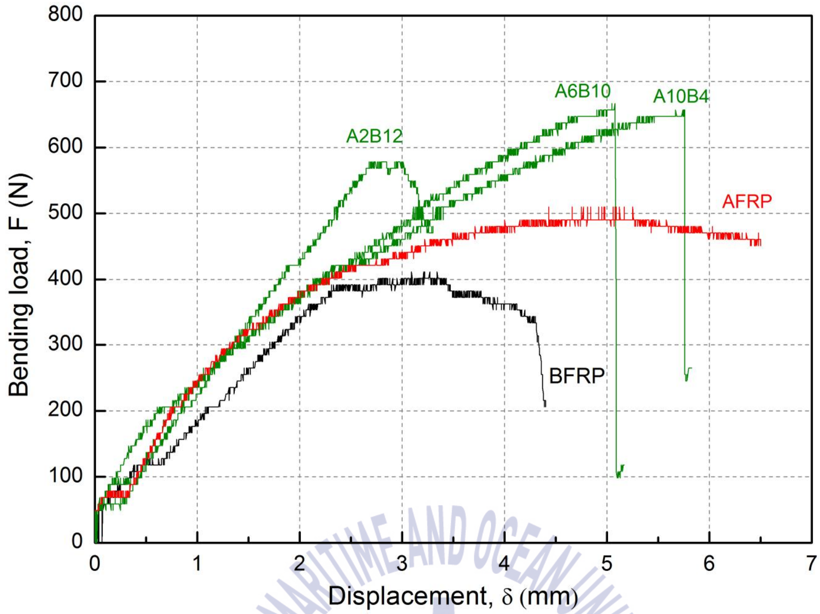


Fig. 10 Effect of aramid content on bending load-displacement curve

3.2. Effects of aramid/basalt HFRP fiber content on mechanical properties

3.2.1. Tensile behavior

6 samples with different ply sequence are made and the laminate code of the samples are shown in Table. 2. Every sample has a same total ply number of 14 and change with the ply sequence of 7 aramid fiber ply and 7 basalt fiber ply. The tensile strength are shown in Fig. 11. For all samples with different ply

sequence, there is no obvious difference of tensile strength and the tensile strength are all in a range of 400 MPa to 440 MPa. The tensile strength was considered to have an association with aramid/basalt ply interface number. The best tensile strength, 436 MPa, was observed in laminate code A which is every single aramid and basalt ply are put alternate with each other. In this situation, the sample has the maximum aramid/basalt interface number of 13. The lowest tensile strength comes out in the laminate code F which is all 7 aramid plies are put in one side and all 7 basalt plies are put in the other side, this ply sequence has the minimum aramid/basalt interface number of 1. Laminate code E exhibited the inconsistent value and it's because the stronger aramid fiber on the outside can protect the basalt fiber and impede the crack propagation.

Table 6 Tensile strength of different aramid/basalt HFRP ply sequence

Laminate Code	Tensile strength/ (MPa)
A	436
B	432
C	417
D	408
E	426
F	408

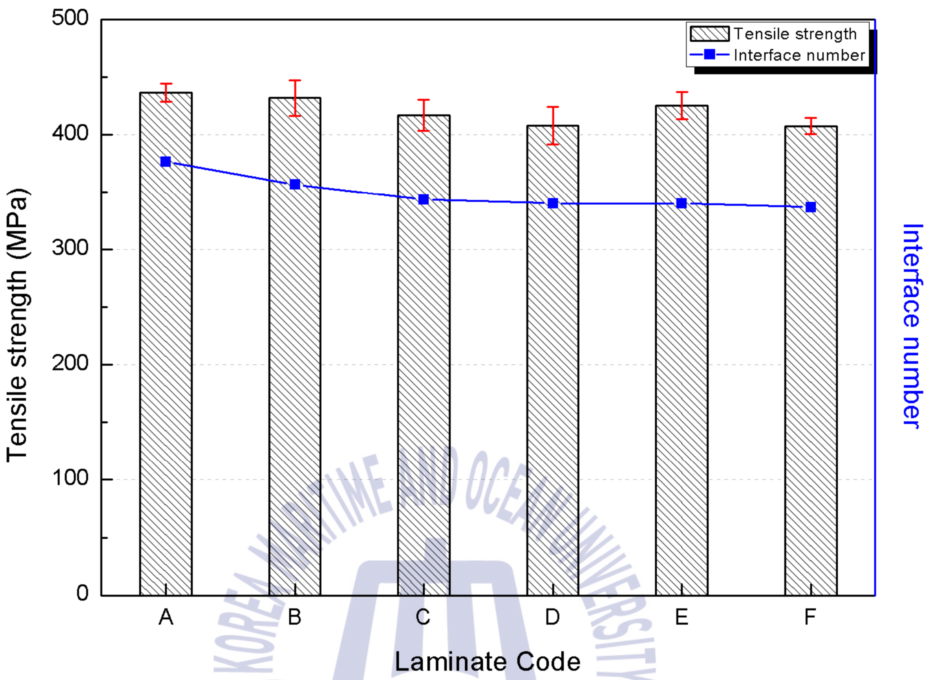


Fig. 11 Effect of ply sequence on tensile strength

3.2.2. Flexural behavior

Samples with different ply sequence which are shown in Table. 2 are produced by aramid and basalt woven fibers for bending test. As for the specimens are all asymmetry, every sample was conducted bending test for both directions. The result was shown in Fig. 12 and the bending load-deformation curve was shown in Fig.

13. The "laminate" represents that the specimens with different ply sequence was tested in the same direction of crosshead motion and laminate code; or the plies of placed specimen from top downwards is just right the same with laminate code. The “Reverse” means the specimens were put reversed and test in the inverse loading direction and symbol “R-” is used in front of the laminate code to represent the reverse situation.

Table 8 Bending strength of different aramid/basalt HFRP ply sequence

Laminate code	Bending strength/ (MPa)
A	296
B	278
C	286
D	332
E	235
F	221

Table 9 Reversed bending strength of different aramid/basalt HFRP ply sequence

Reversed laminate code	Bending strength/ (MPa)
R-A	304
R-B	307
R-C	272
R-D	312
R-E	230
R-F	274

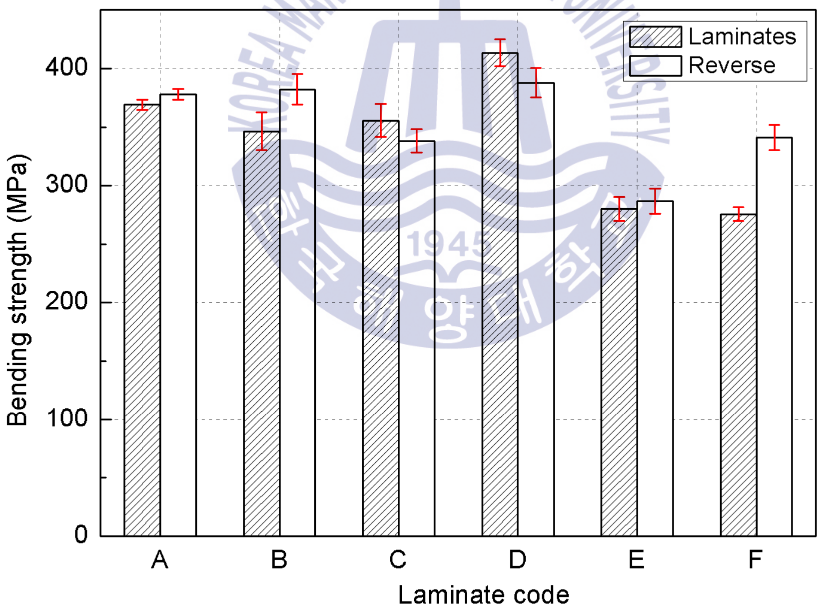


Fig. 12 Effect of ply sequence on bending strength

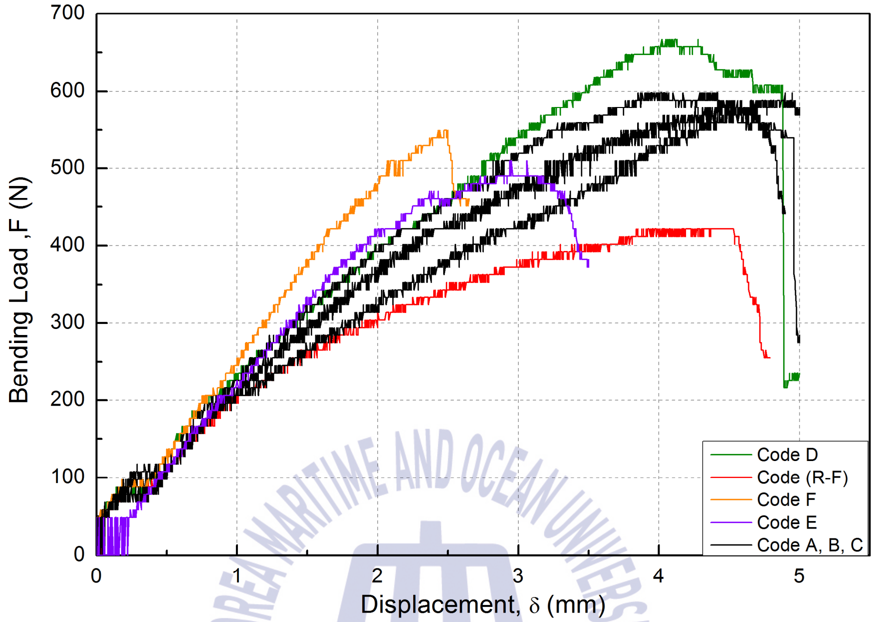


Fig. 13 Effect of ply sequence on bending load-displacement curve

The different ply sequence have great influence of the bending property. Overall, the best bending property was shown in samples with laminate code D which is 414 MPa and the lowest bending strength came out at laminate code R-D which is 286 MPa. For the situation of same ply sequence, different loading direction also lead different consequence. The biggest bending strength distinction was obtained in code F and code R-F, which has the disparity of 55 MPa and the minimum bending strength difference of both loading direction is code A and code R-A, which differs only 9 MPa. The ply sequence of code D and code E also have a huge distinction of bending strength and the only difference of two ply sequence is that at ply sequence of code D, the basalt plies were put in the center and the aramid plies are put on the both sides of basalt ply, while at ply sequence of code E, the aramid plies are put in the center and the basalt plies are put adjacently next to the basalt ply.

Lamination of code F has a linear bending behavior and failure occurred at minor displacement which have the similar behavior with the BFRP while the loading-displacement curve of code (R-F) is totally nonlinear and can endure a lot displacement which is like AFRP. They both have the similar behavior with the bottom part. All ply sequence have the bending behavior between lamination code F and code (R-F). Lamination of code E and D have the almost same behavior at the initial load phase but samples with laminating code E have less displacement before fracture.

3.3. Evaluation of mechanical properties by addition of HNT

Halloysite is a clayey mineral [Al2Si2O5(OH)4·E2H2O], consisting of tubular particles with multi-layered wall structure and mainly used as a sorbent helping in the deactivation of hazardous materials after their uncontrolled leakage as well as a filler in the polymer materials. The bending strength of HNT particle - added aramid/basalt HFRP changed by HNT amount was shown in Fig. 14. There are varying degrees of improvement of bending strength by adding HNT and when the HNT content was 2 wt%, the highest bending strength was shown. In the range of 0~2 wt% HNT content, the bending strength presented a general upward trend but at 3 wt% HNT content the value has a marked fall.

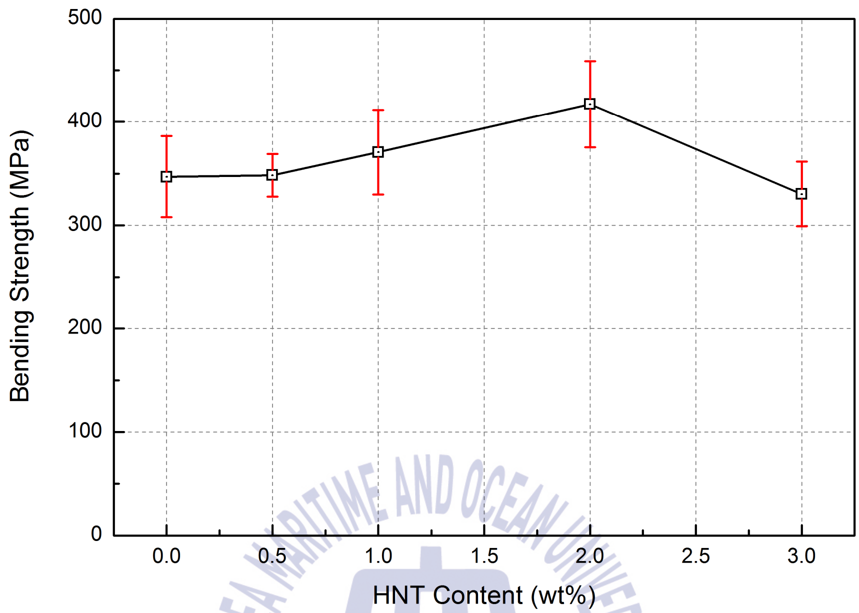


Fig. 14 Bending strength of aramid/basalt HFRP by HNT Contents

The reason for the highest bending strength at 2 wt% is that the reinforcing effect of each layer is the highest at 2 wt% of interlayer interfacial shear strength, which is evidence of reinforcing effect to shear by addition of HNT. However, as a result of previous studies, it seems that the addition of HNT above a certain amount causes the HNT to coagulate due to the high surface energy of HNT, resulting in a decrease in strength. Fig. 15 is an image obtained by measuring the fracture surface with SEM after bending strength test as a result of HNT aggregation. This SEM image can be used to easily identify HNT aggregation [21].

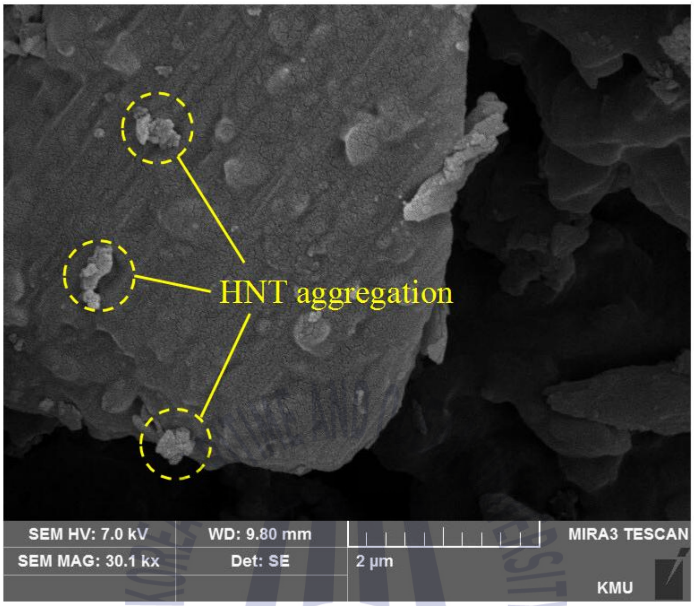
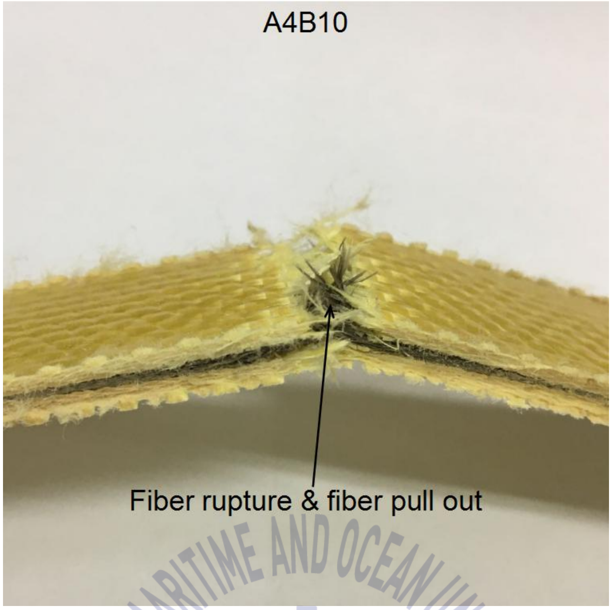


Fig. 15 SEM image of HNT-added aramid/basalt hybrid composites [I Jin U, 2015. *A study on the Interfacial Properties of Nano Particles-contained Carbon Fiber Reinforced Composite Materials*. Doctoral degree. Busan: Korean Maritime and Ocean University.]

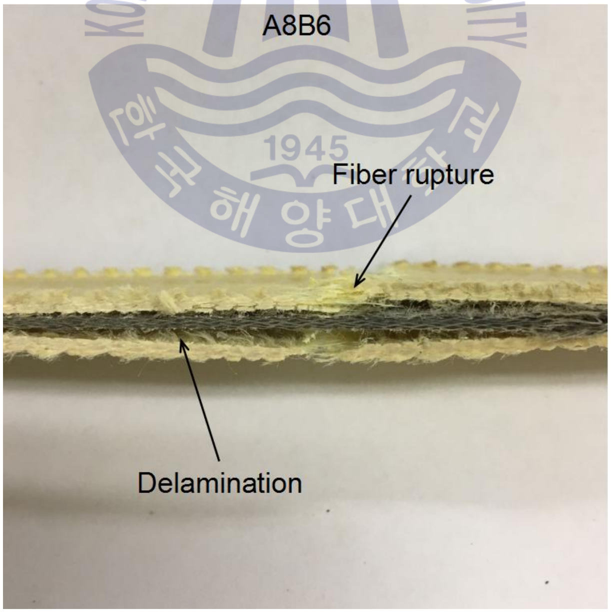
3.4. Aramid/basalt HFRP fracture mechanisms

3.4.1. Tensile fracture mechanism

The fracture mechanism of different fiber content specimens are different. With low and high aramid fiber content, the main fracture mechanism is fiber pull out and fiber rupture, see in Fig. 16(a) and Fig. 16(c). In the equivalent fiber ratio situation, the main fracture mechanism is delamination of aramid layer and basalt layer, debonding of fiber and resin, see in Fig. 16(b). In all situation, basalt fiber always fracture before aramid fiber because its lower elongation at break than aramid fiber, brooming of aramid fiber can be observed in the fracture position. It's obvious to see that delamination and debonding are the main limitation of tensile property in hybrid condition. The surface of aramid fibers has low chemical activity, few polar functional groups and smooth morphology, resulting in the poor interface bonding with the resin matrix and other fiber reinforcement. For increase the mechanism properties of aramid/basalt hybrid composite, it's convinced to increase the number of interfaces and prevent the delamination for better mechanical properties.

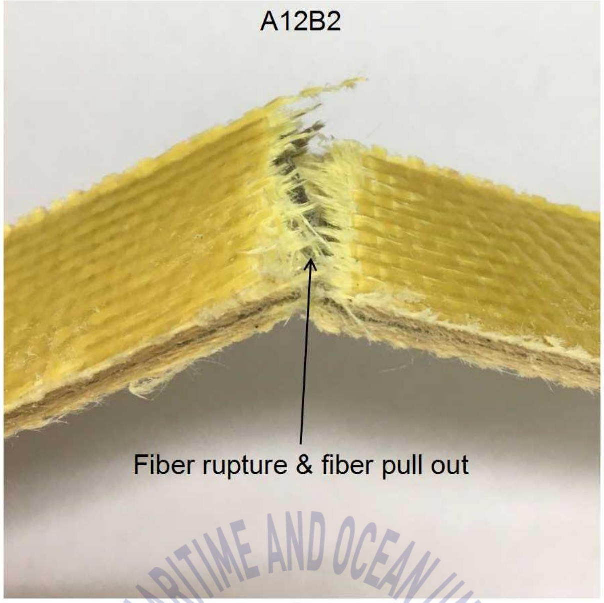


(a)



(b)

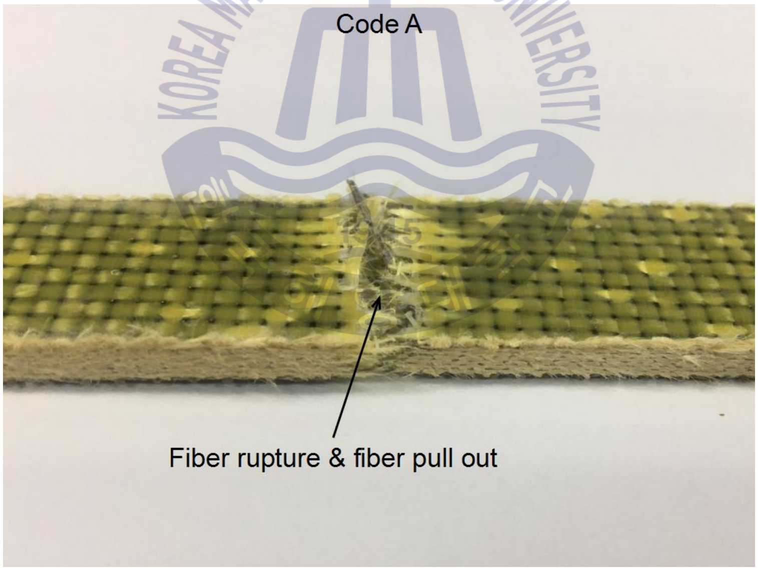
Fig. 16 Fracture morphology of specimens with different fiber content



(c)

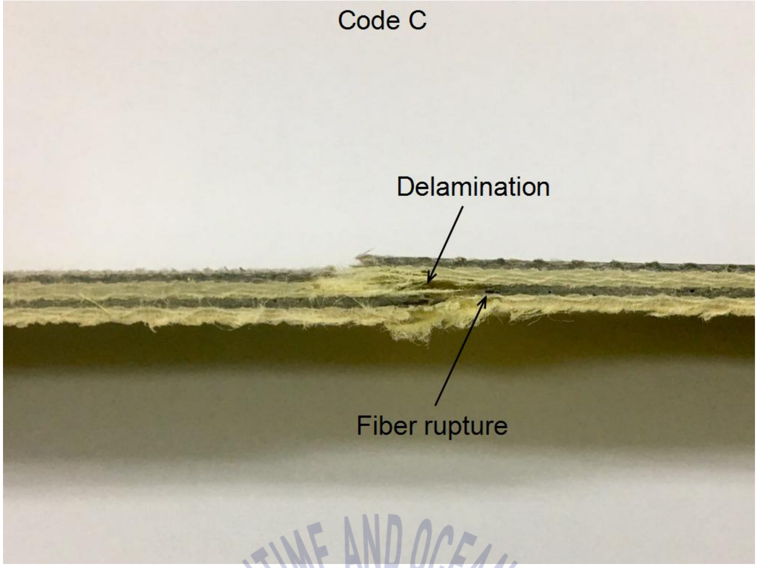
Fig. 16 *(continued)* Fracture morphology of specimens with different fiber content

For the samples of different ply sequence, the tensile strength have generally positive correlation with the aramid/basalt interface number. For samples with laminate code A have no observation of delamination and broom-like fracture morphology but are all broke because of fiber rupture. For other samples, with the decreasing of aramid/basalt interface number, it's more likely to observe delamination and debonding of reinforcement and matrix. Samples with laminate code F which only have one aramid/basalt interface have very severe delamination of aramid ply and basalt ply. The positive correlation of tensile strength and aramid/basalt ply interface number are probably because of low fibre/matrix adhesion and low interfacial adhesion of aramid due to chemical resistance and more interface number can enhance the binding strength of aramid fiber with basalt fiber and epoxy resin. The fracture morphology was shown in Fig. 17.

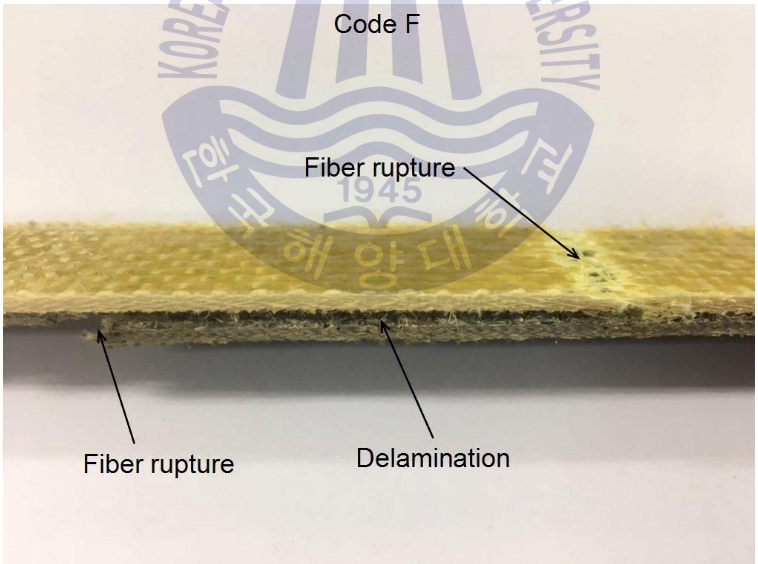


(a)

Fig. 17 Tensile fracture morphology of different ply sequence



(b)

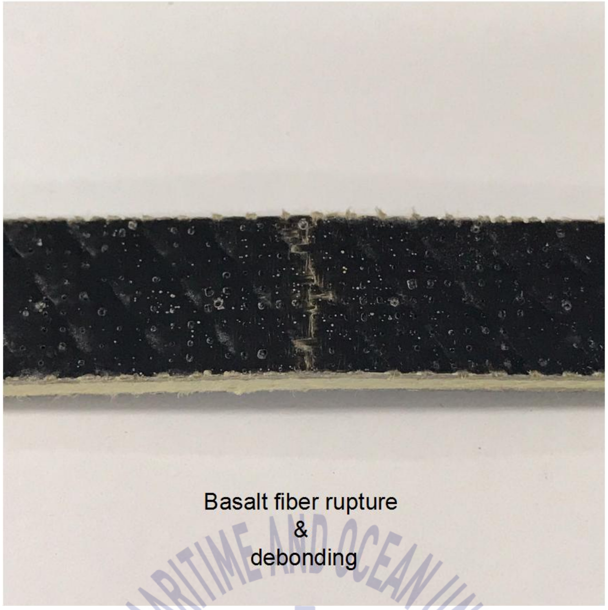


(c)

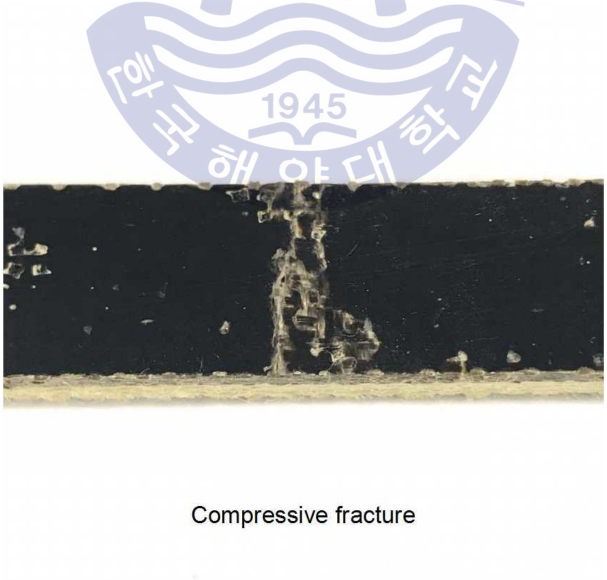
Fig. 17 *(continued)* Tensile fracture morphology of different ply sequence

3.4.2. Flexural fracture mechanism

During the bending test, the specimen can be regarded as a beam in 3 points bending test and during the test, the uppermost plane has the maximum surface compressive stress and the bottom plane has the maximum bending moment and failure occurs there. Aramid fiber has both better compressive stress and tensile stress than basalt so that the laminating structure of basalt plies in mid and the aramid plies covered in both can prevent the failure caused in upper and bottom and can provide the best bending property and the position of basalt plies can certainly influence the bending strength. Fig. 18 shows the different fracture morphology of samples with different basalt ply positions. The fracture morphology of the specimens which have basalt fiber on the bottom side is the bottom-side basalt fiber rupture and debonding with the resin, see in Fig. 18 (a); the basalt fiber on the top situation was observed upper basalt fibers conducting compression failure and resin wrinkle, see in Fig. 18 (b). When the basalt fiber plies are put in the middle of aramid plies, the main fracture mechanism is the middle part basalt fiber rupture, see in Fig. 18 (c).

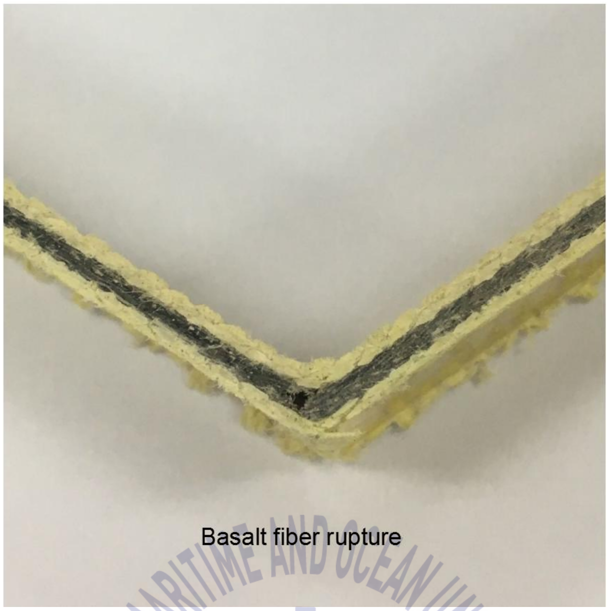


(a)



(b)

Fig. 18 Fracture morphology of samples with different basalt ply position



(c)

Fig. 18 *(continued)* Fracture morphology of samples with different basalt ply position

4. Conclusions

With a high mechanical performance material, hybrid composites were supplied by lamination design of aramid/basalt fabric. Diverse aramid/basalt hybrid composites were soundly manufactured using the VaRTM process. The effect of different fiber content and ply sequence on the mechanical properties was investigated by the tensile and bending tests. 6 samples with different fiber content, 6 samples with different ply sequence and neat AFRP, BFRP, all 14 types composite of different laminates are prepared for the tests. After all test, 5 samples with HNT particles added in matrix are made aimed to improve the flexural ability.

In the different fiber content situation, aramid/basalt hybrid composites all have the tensile strength and modulus of elasticity between the AFRP and BFRP. In the range of 0~30% and 50~100% aramid fiber relative weight content, the tensile strength rises together with the aramid content but in 30~50% aramid content the tensile strength goes down. With low and high aramid fiber content, the main fracture mechanism is fiber pull out and fiber rupture while in the equivalent fiber ratio situation, the main fracture mechanism is delamination and debonding. During the bending test, all hybrid composite have the better bending strength compare to neat AFRP and BFRP and the bending strength reached the maximum point 424 MPa at 70% aramid fiber content. All hybrid specimens have approximate linear elastic behavior after bending loading and the more basalt fiber content they have, the more those specimens have a linear bending behavior.

In the different ply sequence situation, the tensile strength of aramid/basalt hybrid composites have no significant difference but it generally have the positive correlation with the number of aramid/basalt ply interface. The best tensile strength 436 MPa was shown at laminate code A which has 13 interfaces and the lowest tensile strength was observed at laminate code F which only have 1 interface. It is may because of the low interfacial adhesion of aramid fiber/matrix. In the bending test, every ply sequence was tested in both directions and for the samples which have the same ply sequence, the direction in which fewer basalt plies are put on the more bending moment side and more aramid plies are able to endure the bigger strain are all have the better bending strength than the other direction. The ply sequence in which the aramid plies are put in the plane and the basalt piles are used as the core has the best bending strength 414 MPa. The extent of how much the aramid fibers are approaching the opposite side of bending pressure point can improve the bending strength comparatively and can be a un-ignorable design consideration.

Adding HNT additives can improve performance to a certain extent but too much HNT can cause the aggregation and limit the bending strength.

Overall, aramid/basalt HFRP has tensile properties between neat AFRP and BFRP, more aramid/basalt interface can improve the tensile properties limitedly. HFRP with 70% relative aramid fiber weight content has the best bending strength and the laminate pattern in which the basalt piles in the core and the aramid piles in outer plane can provide the best bending property in different ply sequence situation. Additionally, this ply sequence has aramid fibers covering all basalt, the aramid fiber on the surface can provide an excellent corrosion and chemistry resistance and this can be the reference options for the design consideration of marine usage.

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