Study on Cavitation Erosion of Composite Materials for Marine Propeller

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SUMMARY

We are developing the new propeller made of composites that have advantages for the energy conservation of ships. However, we found that fibre reinforced plastics are not resistant to erosion by cavitation to which the propeller is exposed. In this study we investigated the cavitation erosion of various kinds of composite materials.

Keywords: marine propeller, cavitation, erosion, composite, FRP

INTRODUCTION

Composites have high specific strength and stiffness, and are used in a wide variety of fields, from aircraft to vehicles and wind turbine blades. In marine-related areas, while composites are widely used in small-scale crafts, they are not used in large-scale crafts; the use of composites is even less widespread in the field of propellers used as propulsion devices. However, research and development[1,2)] of propellers using composites are advancing. The backdrop to this advancement is the fact that composites can provide a wide variety of special characteristics that metal materials cannot. In terms of costs, as well, the diffusion rate of composites is rapid; technology advances yearly and the costs of composites are becoming cheaper. It can be said that composites should be given attention as materials which can supplant conventional metal materials.
As composite propellers are applied to marine propellers, concerns arise regarding environmental degradation caused by operation within seawater, as well as damage caused by impacts with floating objects, etc. Furthermore, it is desirable that a propeller would have erosion resistance to exposure to cavitation during propeller operation. Figure 1 shows a photograph of an actual carbon fibre reinforced plastic (CFRP) propeller with cavitation erosion damage. The surface coats and layers are peeled, and the damage has extended even inside the laminate. At present, we can say that the cavitation erosion problem for composite propellers remains unsolved[3)]; in order for composite propellers to become further widespread, it is necessary to analyze the erosion mechanism and to develop the method to prevent it.
In this study, we prepared several types of composites, carried out cavitation tests using a magnetostrictive ultrasonic transducer, performed surface observations, measurements of loss amounts and observations of fragments of loss materials caused by erosion, and then compared the erosion resistance of composite materials prepared.

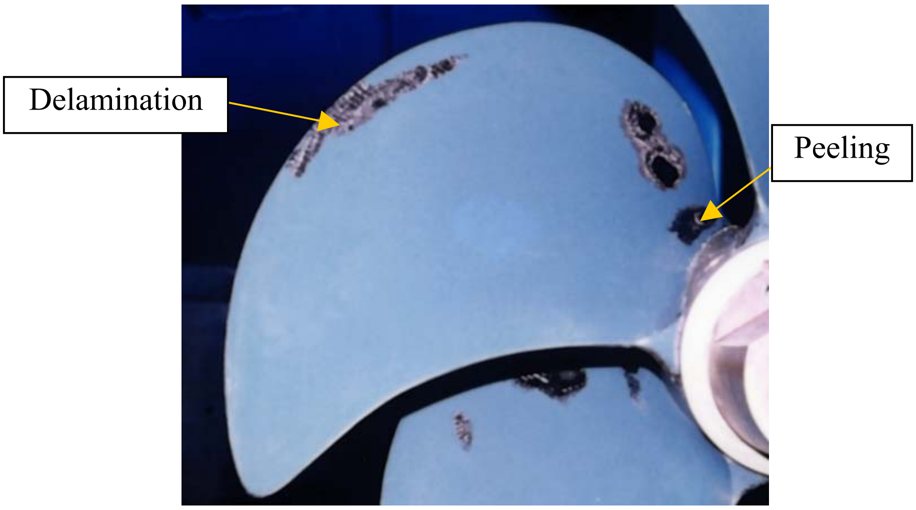

Figure 1 Damaged propeller due to cavitation erosion

EXPERIMENTAL PROCEDURES

Test Specimens

Test specimens were of the nine types shown in Table 1. There were three types of reinforced fibres. Those were carbon fibre (CF), glass fibre (GF) and aramid fibre (AF). For CF, there were two types of textiles that were fabric and multi-axial, and two types of fabrication processes that were vacuum assisted resin transfer molding (VaRTM) and prepreg autoclave method. In the results, we had three CFRP specimens, namely CF-Fab-VaR, CF-MA-VaR, and CF-Prepreg. In the case of GF, we didn't use any prepreg, so there were two specimens, namely GF-Fab-VaR and GF-MA-VaR. Then we had two specimens made of AFRP whose fabric plies were two and four, respectively. The fabrication process used for AFRP was also VaRTM. In addition, we prepared a specimen made of only epoxy resin and one type of aluminum bronze molded NAB (CAC703), which is used for marine propellers.

Table 1 Specimens

Name	Fiber	Textile	Matrix	Fabrication process
CF-Fab-VaR	Carbon	Fabric	Epoxy	VaRTM
CF-MA-VaR	Carbon	Multi-Axial	Epoxy	VaRTM
CF-Prepreg	Carbon	Fabric	Epoxy	Prepreg
GF-Fab-VaR	Glass	Fabric	Epoxy	VaRTM
GF-MA-VaR	Glass	Multi-Axial	Epoxy	VaRTM
AF2-Fab-VaR	Aramid	Fabric	Epoxy	VaRTM
AF4-Fab-VaR	Aramid	Fabric	Epoxy	VaRTM
Epoxy-VaR	N.A.	N.A.	Epoxy	VaRTM
NAB	N.A.	N.A.	CAC703	Casting

Test Equipment for Cavitation Erosion

Using the magnetostrictive ultrasonic transducer device, we conformed the test conditions to ASTM-G32[4)], and carried out an opposed cavitation erosion test[5)]. The transducer is shown in Fig. 2 and its vibrating frequency and vibration amplitude (peek

to peek) were 19.5 kHz and 50 μm, respectively.
In this device, ultrasonic longitudinal oscillation causes pressure fluctuations to arise at the tip of a vibratory horn immersed in liquid, which in turn gives rise to cavitation. The test situation is shown in Fig. 3. For this test, we positioned a test specimen at a distance of 0.5 mm from the vibratory horn tip, and then caused the cavitation produced by the vibratory horn to collapse on the surface of the test specimen.

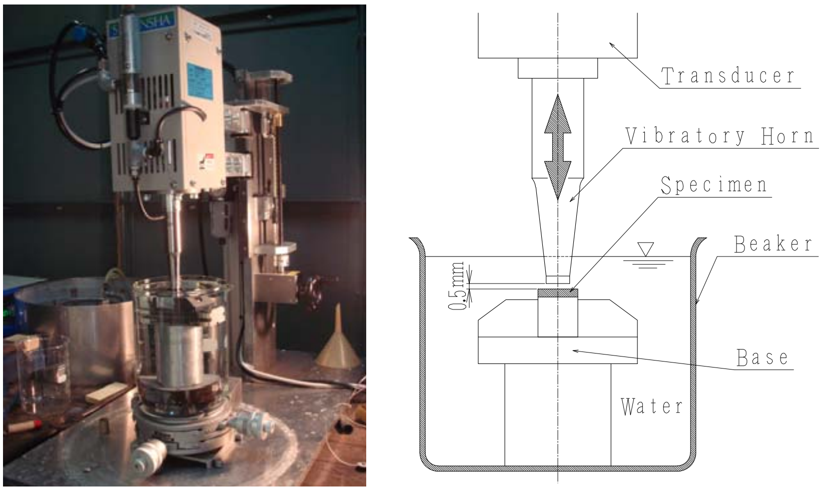

Figure 2 Test equipment

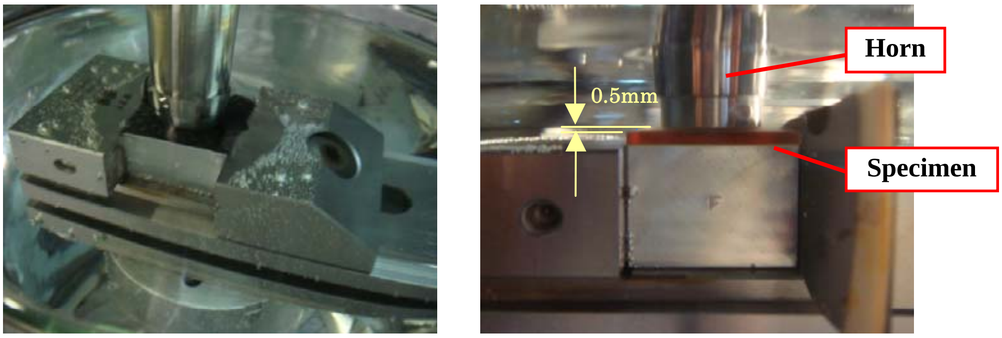

Figure 3 Test situation and condition

Test Procedures

For the positioning conditions of the vibratory horn and the test specimens, the vibratory horn was immersed in the water, and the specimen was placed in a direction counter to the vibratory horn, at a distance of 0.5 mm from the vibratory horn tip. All of the water used was ion-exchanged water, including the water used to clean the equipment.
The specimens were exposed by cavitation totally for 120 minutes. At every 15 minutes, the mass of the test specimen was measured by a precise mass measurement device, and the surface of the test specimen was subjected to a visual and a microscopic examination (photographed using a digital camera). The fragment of loss materials was obtained from the test water by filtering system (mesh size: 0.45 μm). The filtering system is shown Fig. 4.
Due to stirring and the replacement of the water every 15 minutes, the temperature of the water during testing was 21 ± 4 degrees Celsius.

Figure 4 Filtering system

EXPERIMENTAL RESULTS

Loss Amounts Due to Erosion

Figure 5 shows the volume loss due to cavitation erosion of each material with respect to exposure time. The volume losses were determined by dividing the mass loss by the specific gravity. From Fig. 5 we can see that for all materials loss amounts increased with time. Aluminum bronze (NAB) displayed the smallest loss amounts and even after 120 minutes of test time, there was almost no loss. The composites used in these tests were categorized into four groups according to degree of loss. In order from smallest loss amount, the categories are: Group 1, AF4-Fab-VaR and AF2-Fab-VaR; Group 2, CF-Fab-VaR and Epoxy-VaR; Group 3, CF-MA-VaR, GF-Fab-VaR, and CF-Fab-Prepreg; and Group 4, GF-Fab-VaR, which displayed the most loss amount.

While Group 3 and Group 4 in that epoxy resins were reinforced by GF or CF lost more than about twice as much as Epoxy-VaR, Group 1 in that the resins were also reinforced by AF was stronger than the original epoxy resin of Group 2 in the cavitation erosion. This means AF reinforcement could improve the erosion resistance of epoxy resin, although CF and GF might reduce it.

The loss amounts were difference from combination of the reinforced fibres, the resin, the textile and the fabrication processes. At the first, influence of the textile was considered about as same fibre. In case of CFRPs without CF-Fab-Prepreg, the loss amount for fabric was decreased to approximately 0.6 time of multi-axial. In case of GFRPs, the loss of amount for fabric was increased to approximately 1.5 times of multi-axial. Thus, the loss amounts of GFRPs and CFRPs were reversing with those textiles. It is considered that the influence of the loss amounts is not only the textiles but also other reasons. One of the reasons might be the interface strength between the fibres and the resins. Next is an influence of reinforced fibres as the same textile of fabric. The loss amounts for AFRPs, were the smallest than another FRPs, are made base values. The amounts of CF and GF were each approximately 2.5 times and 6 times of AFRPs, respectively. Regarding the different fabrication processes of CFRPs, the loss amounts for CF-Fab-VaR were approximately 0.6 time of CF-Fab-Prepreg.

By performing AF lamination on the surface layer using GF-Fab-VaR as the base, which had the poorest erosion resistance, the loss amounts for AFRPs were approximately one sixth of that of GF-Fab-VaR, which is to say that erosion resistance was improved. Regarding the influence of the thickness of the AF layer, we can see that erosion resistance was slightly higher for the AF4-ply materials than for the AF2-ply materials.

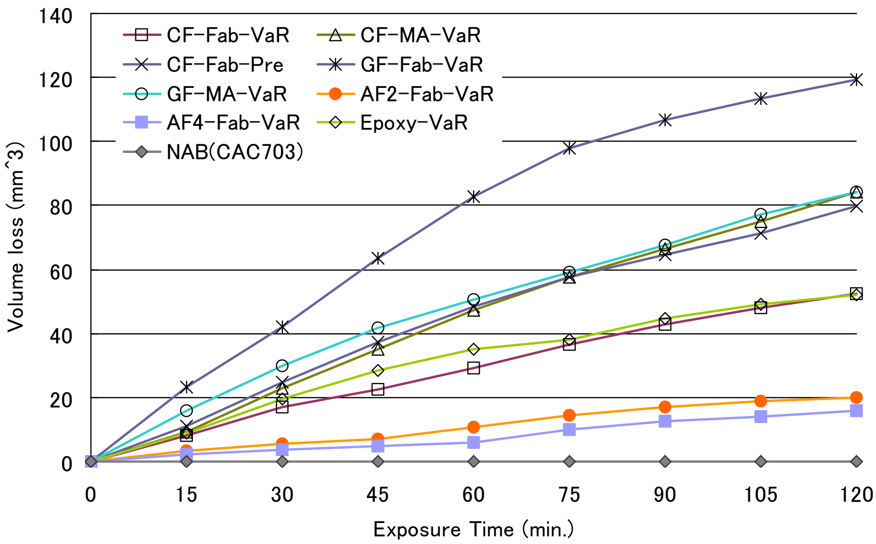

Figure 5 Volume loss for exposure time

In Fig. 6, we found the loss rate for every 15 minutes of time, based upon the loss amounts in Fig. 5 to evaluate the progress of the erosion. In Fig. 6, we can see that the loss rate was reduced in conjunction with the exposure time, and that each type of material eventually converged after fluctuating up and down at arbitrary rates. GF-Fab-VaR displayed both the highest loss rate, as well as the largest reduction ratio. On the other hand, although the loss rate for AF was the slowest, it can be seen that AF also displayed a large proportion of changes in increased and decreased rate in conjunction with time. The great one of the loss amounts was, the loss rate at the beginning was rapid, and the loss rate was gradually slow. It seems that the loss rate became smaller with time because the collapse hole became deep and the influence of cavitation decreased. It can be considered that the erosion resistance by an opposed cavitation erosion test is able to estimate the degree at the initial stage.

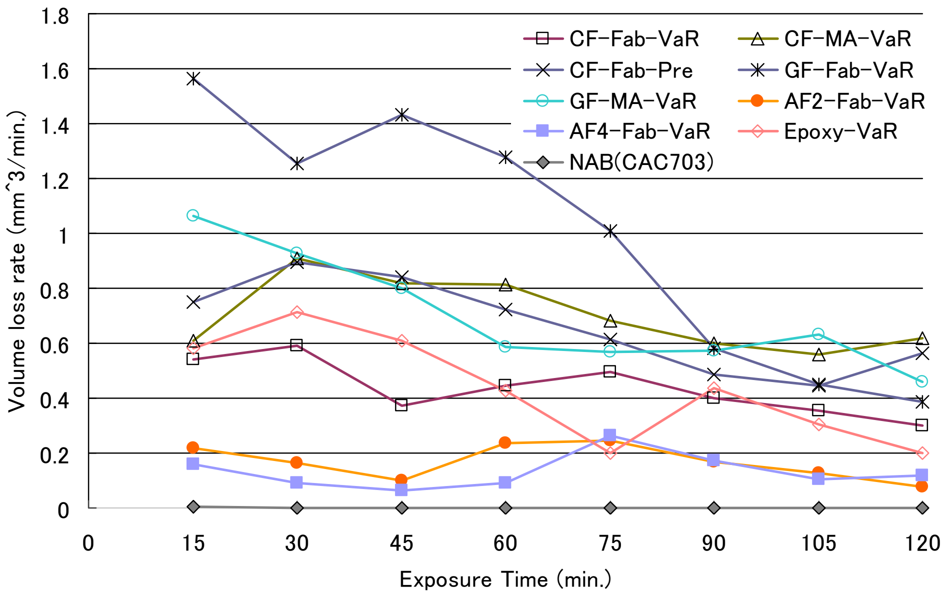

Figure 6 Volume loss rate for exposure time

Progress of Cavitation Erosin

Figure 7 shows photographs of the surface condition of each material, taken every 15 minutes.

For each material, it can be observed that damage is being done in the circular fashion of the vibratory horn tip. Even after 120 minutes had elapsed, NAB was still only slightly roughened. On the other hand, in keeping with the changes in loss amount shown in Fig. 5, it can be seen that, for composites, the depth of loss deepened with the exposure time. This loss condition was due to the resin peeling off during the early stages of testing; the cavitation reached to the reinforced fibre, the fibres for CFRPs and GFRPs were broken as each strand disintegrated, and the fibres for AFRPs were curled and remained on the damaged surface. Closer observation is as follows.

Regarding the GFRPs, both types lost their surface resin and the fibres themselves were broken, and the collapse surface looked as though it had been scratched out at random, and there was severe unevenness on the surface. For the GF-Fab-VaR, from 15 to 30 minutes both the resin and the fibres were broken; corrosion was quite rapid, and similar to loss amount changes due to erosion. On the other hand, the fibres of the GF-MA-VaR were broken from 60 to 75 minutes. This shows that there are apparent differences between the two type of textiles.

Although the loss rates for the CFRPs were different, in all three types corrosion progressed evenly, in the direction of the materials' thickness and for each layer alike. However, from 60 to 75 minutes the loss for CF-MA-VaR became random, and unevenness appeared.

Both AFRPs whitened and the threads gradually came unraveled; these unraveled threads formed entangled fibrils, which grew ever larger and looked as if they might fall off. The growth of these fibrils became visible from between 45 and 60 minutes for AF2, and from between 60 and 75 minutes for AF4, which is to say that there was a time difference between the two types. The times for both types match the increased loss rate times from Fig. 6; it can be considered that the loss amount becomes greater when the loss rate times increase thusly.

For the loss condition for epoxy resin only, which is a matrix resin, it could be observed that the material whitened, and then particles formed, grew larger, peeled and fell off. Although this whitening phenomenon was the same as for the AFRPs, it can be considered that, because the epoxy is not a fibre, the particles fell off and the loss amount was greater than for the AFRPs.

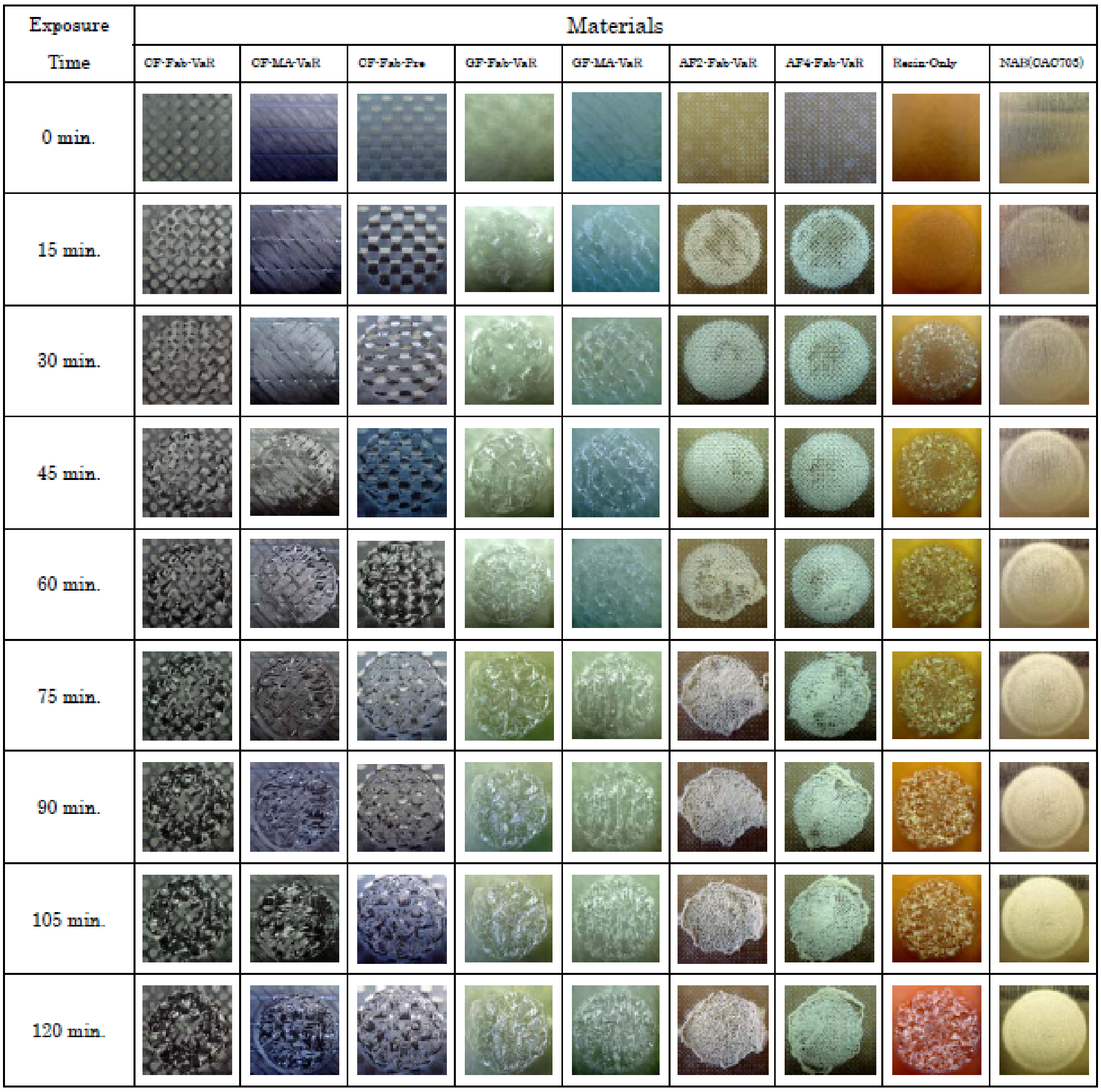

Figure 7 Surface appearances of materials for each time

Collapse Process for FRP under Cavitation Erosion

Progress of cavitation erosion for FRP was observed in Fig. 7. In this section, we conducted microscope observation to clarify the collapse process for FRP under cavitation erosion, especially for the collapse surface and the peeled fragments of specimens.

Figure 8 shows microphotographs for the collapse surface exposed for 60 minutes and the peeled fragments exposed for between 45 and 60 minutes of epoxy resin-only.

Whitish things which were crushed the resin to small were seen in the peeled fragments photos. And also comparatively large particles were observed. Consequently, the collapse process for epoxy resin under cavitation erosion are, at the first whitening phenomenon occurs, gradually collapsed and then particles formed, grew larger, peeled and fell off.

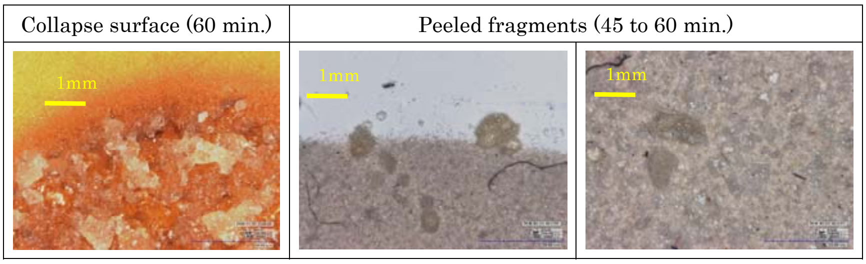

Figure 8 Collapse surface and peeled fragments of epoxy resin-only by photomicrography

Figure 9 shows microphotographs of CFRPs for the collapse surface exposed for 60 minutes and the peeled fragments exposed for between 45 and 60 minutes. We observed the collapse surface and the peeled fragments in detail by the microscope. For all of CFRPs, it was observed that the peeled fragments were the fibres, the resins and also the fibre bundles with the resins. The size of peeled fragments were approximately 100 μm fibres were dominant. The length of peeled fragments of CF-MA-VaR existed over 4 mm which was longer than the fabric series

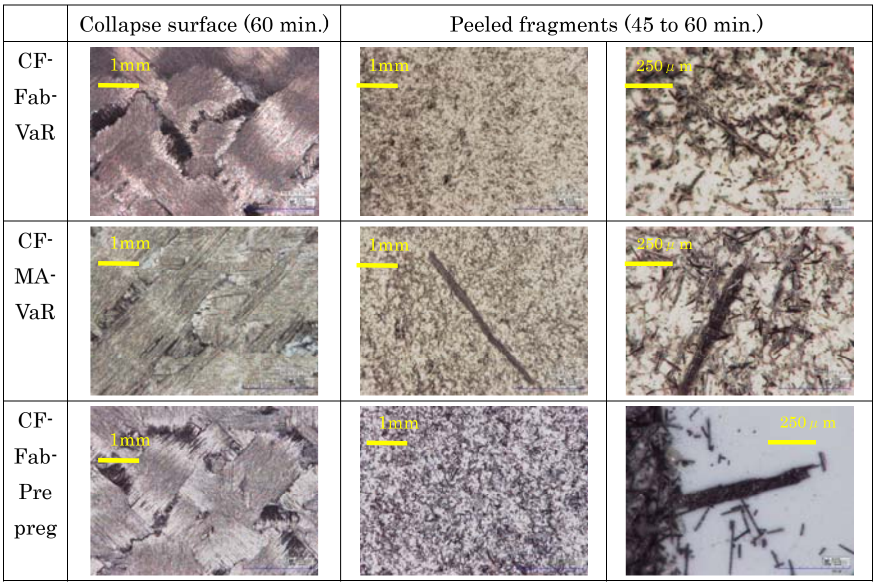

Figure 9 Collapse surfaces and peeled fragments of CFRPs by photomicrography

On the other hands for GFRPs, Fig. 10 shows microphotographs of the collapse surface and the peeled fragments same as condition of Fig. 9. Collapse surface photos exhibited both fabric and multi-axial textiles were scratched out at random. And the peeled fragments photos showed the fibers and the resins were dominant but the fibre bundles were few. The size of the peeled fragment for fabric and multi-axial textile were similar, furthermore the fragments were divided the fibres and the resin, the length of the fibres were over 1 mm were dominant. This trend is different from those of CFRPs, the peeled fragments for CFRPs had the fibre bundles a little, but those of GFRPs had hardly the bundles and were mainly longer fibers than CFRPs. In this test, it is considered that the fibres of CFRPs had been better adhesion with the fibres and the resins than that of GFRPs. Erosion resistance of CFRPs was superior to that of GFRPs showed in Fig.5. Therefore, it conjectures that erosion resistance is improved when the adhesion between the fibre and the resin are stronger.

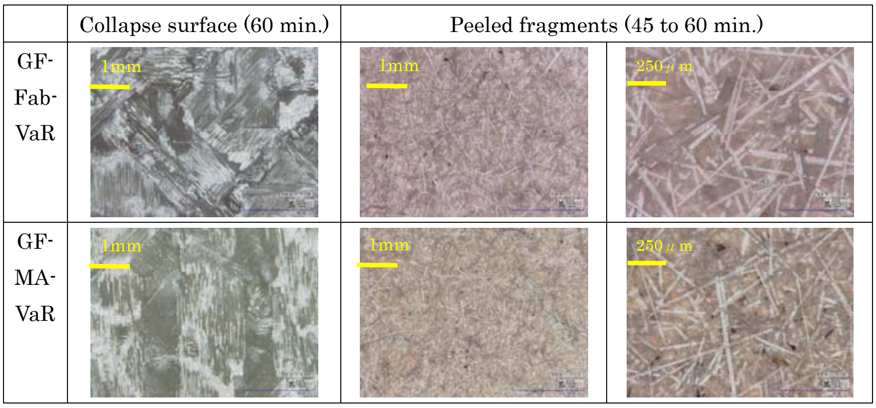

Figure 10 Collapse surfaces and peeled fragments of GFRPs by photomicrography

Finally, AFRPs showed the strongest erosion resistance among FRPs. Figure 11 also shows the collapsed surfaces and the peeled fragments for AF4-Fab-VaR. The exposure time is same as Fig. 8 and 9. The collapse surface and the peeled fragments for AFRPs were different from CFRPs and GFRPs. The surface of AFRP was covered with something like cocoons that were formed entangled fibrils by the observation of the collapse surface. It can be considered that the reason that the loss amounts for the AFRPs were less than for the other composite materials was that the fibrils covered over the surface, absorbed the impact waves during cavitation collapse and made it more difficult for loss to progress. The peeled fragments photo shows that the fibres were almost fuzzy and were hardly with a complete form, and also the lump which was entangled the fibres, the fibrils and the resin were able to observe. The lumps fall off during collapse process.

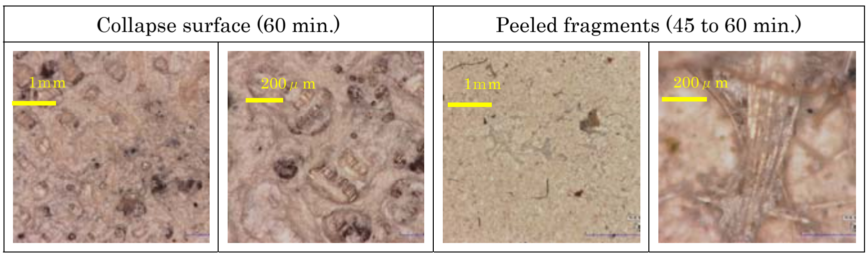

Figure 11 Collapse surface and Peeled fragments of AF4-Fab-VaR by photomicrography

CONCLUSIONS

In this study, the erosion resistance of GFRPs was lower than that of CFRPs. The peeled fragments of CFRPs and GFRPs consisted of the fibres and the resins. In the case of CFRPs, there were also the fibre bundles with resin, while there were few fibre bundles in the case of GFRPs. We also found that most of the fibres of GFRPs were longer than those of CFRPs. The erosion resistance of FRP under cavitaion may be influenced by the adhesion between the fibre and the resin.

AFRPs showed the strongest erosion resistance among FRPs and the collapse process differed from CFRPs and GFRPs. It is considered that the fibrils covered over the surface, absorbed the impact waves during cavitation collapse and made it more difficult for loss to progress.

However, the erosion resistance of aluminum bronze (NAB) which is frequently used for marine propellers is much stronger than those of all FRPs.

In order to improve the erosion resistance of FRP, it is important to understand the erosion mechanism under the cavitation and to find the effective configuration of composite materials

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