Composite Lines for Kelp Aquaculture

Emma Kross, Garrett Frohman, Haley Fong, Olivia Luthringer, Rachel Barden

TECH 797: Undergraduate Ocean Research Project

Dr. Igor Tsukrov & Zach Moscicki

May 12, 2021

Acknowledgments

We would like to give thanks to the NH Sea Grant and the UNH Mechanical Engineering Department for their generosity in funding and supporting this project through the Undergraduate Ocean Research Projects class. We would also like to acknowledge the US Department of Energy's ARPA-E program for funding the project (award no.DE-AR0000923) for which this work was a component.

Abstract

Ropes from offshore kelp farming have the potential to increase the risk of entanglement to marine mammals such as the North Atlantic Right Whale. In an effort to mitigate these risks, researchers at the PNNL Marine and Coastal Research Laboratory and Pete Lynn at Otherlab proposed the idea to replace fiber ropes in aquaculture systems with composite lines. This project is part of a larger research project funded by DOE ARPA-E called *Continuous, High-Yield Kelp Production*. Our group wanted to identify a composite-based product that could act as a tension bearing line and break if encountered by a large marine animal, like a whale, but also be strong enough to support the growth of kelp on it and withstand the force of the ocean. The research over this past year has focused on TUF-BAR, a fiberglass rebar. The mechanical properties of these bars eliminate marine mammal entanglement by breaking as a result of an interaction, therefore mitigating injuries. By breaking instead of trapping a marine mammal, this composite line will reduce the risk of entanglement and potential death due to reduced mobility, inability to feed or inflammation. This research focused on the biological and engineering aspects of using composite lines. Biological objectives include identifying biofouling species that accumulated on the composite lines, researching how the biofouling organisms could affect the composite materials and kelp growing on the lines, looking into kelp holdfast attachment, and completing an experiment to collect data on how kelp and biofouling grows on the composite material compared to nylon and polypropylene ropes which are typically used in kelp aquaculture systems. Engineering objectives focused on the mechanical performance of these rods, durability of the rods and strength of the attachments investigated by laboratory testing (tensile, fatigue, microstructure), and field-testing. Microscopic analysis of cross sections from the exposed rod showed possible damage after nine months of deployment in the water.

1. Introduction

When designing aquaculture systems in coastal areas, risk reduction to the ecosystem is of utmost importance. Ropes are commonly used in kelp aquaculture, but they have the potential to pose an entanglement threat to marine mammals such as the North Atlantic Right Whale. Entanglement can cause harm to the kelp farm itself in the form of damaged property and ruined kelp crops, as well as immense physical harm and even death to entangled marine mammals. One potential solution to this problem is to replace the ropes in kelp farms with rigid rods that break in the event of a whale interaction, allowing the animal to free itself with minimal harm. Our team is investigating the use of TUF-BAR, a type of rebar composed of vinyl ester resin and fiberglass, as a cultivation line for growing kelp. For TUF-BAR to be a suitable material to be used in kelp farms, it must be strong enough to withstand normal ocean conditions, ideally for 5-10 years, but fragile enough to break in the event of a whale interaction. It must be nontoxic to marine life around it and to the kelp growing on it, and it must be able to sustain kelp growth. Part of the challenge is also to employ terminations for the rods which do not create stress concentrations that would cause it to fracture or degrade.

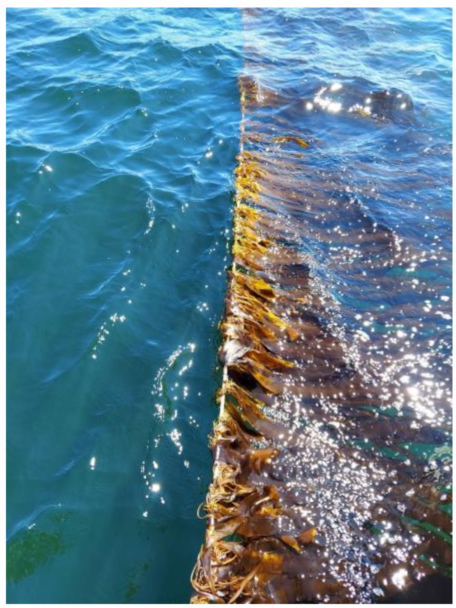


Figure 1. Sugar kelp for aquaculture growing on TUF-BAR line in Saco Bay, Maine

1.1 Danger in Marine Mammal Entanglement

Offshore aquaculture is an up-and-coming practice that could possibly reduce humans' effect on wild marine life and ecosystems. Aquaculture lines have the potential to result in damage to marine animals, so our project aimed to learn how to limit entanglements and ensure interactions do not result in death if they do happen. Factors such as line type, area implemented, and types of animals near the aquaculture system can affect how deadly these interactions are, or if they occur at all. As an example, New Zealand has conducted large scale aquaculture projects, and are doing a lot of research on how large-scale system could affect local ecosystems (Clement 2013). Knowing the area before installing any gear will allow for better understanding of the impact that the system will have and can give insight on future designs to minimize impacts. There are multiple parameters to consider that affect entanglement including the color of the line, the diameter of the line, line material, line strength and tension. Another factor to consider for the potential to cut a whale is the age of the line being used. Newer lines have less fraying of material and were smoother overall so they left fewer cuts in whale interactions (Woodward 2006).

Figure 2. North Atlantic Right Whale entangled in fishing gear off the coast of Canada (Source: NOAA, Peter Duley)

1.2 Background in Macro Algae Cultivation

The cultivation of seaweeds is attractive for food and non-food applications, as it does not compete with agricultural crops for land or fresh water and generates a high yearly biomass yield. Accordingly, seaweed cultivation is often considered to be the most environmentally friendly form of aquaculture, with a number of ecosystem and bioremediation services offered by the seaweeds. In European temperate regions, the highest growth per day of kelp happens in early Autumn and Spring, when daylight is abundant. Previous studies have shown that early deployment in Autumn and delayed harvest in Spring can provide substantial yield while also negating the problem of biofouling that happens later in the Spring. The timing of recruitment of biofouling species on farmed kelps has shown to follow seasonal patterns where species accumulate towards the end of the cultivation period, and typically coincides with an increase in water temperature. Wave exposure and/or water current could be an important factor for selecting an aquaculture site to avoid biofouling (Visch 2020).

2. Field Performance of Composite Lines Compared to Standard Fiber Rope

There has been no prior research into the long-term effects of ocean conditions on the TUF-BAR rebar. It is most commonly used as an alternative to steel rebar for construction projects, and is advertised as being “corrosion-free,” “1/4 the weight of steel, superior in tensile strength, non-magnetic, and non-conductive" [6]. These qualities led our team to identify TUF-BAR as a potential solution to the problem we are trying to solve. The next steps were to experiment with TUF-BAR samples that were exposed to seawater and test their performance and their comparability to ropes in aquaculture systems. Kelp growth on the TUF-BAR lines was tested on a small composite line structure at the UNH Aqua Fort, which was left in the seawater for 9 months. Comparative experiments are also being carried out to look at kelp growth and biofouling on the TUF BAR lines versus standard fiber ropes used in aquaculture systems. It is important that the holdfasts of the kelp are able to secure themselves effectively onto the surface of the composite, and that the composite does not have biofouling that greatly inhibits kelp growth. Further studies on kelp holdfast will need to be conducted. Observations from a field study (outlined in section 3.4) indicated that the biofouling accumulation and kelp growth on the TUF-BAR lines were similar to growth on nylon and polypropylene ropes. The strength of TUF-BAR after long-term exposure to ocean water is unknown, but there have been several studies on the effects of seawater on the strength of epoxy resin and vinyl ester composites. TUF-BAR is composed of vinyl ester resin and fiberglass, and based on findings from our literature review research (Appendix B), we can expect the fatigue life when exposed to seawater to be between 62-85% shorter than its dry fatigue life.

2.1 Fatigue Testing

Students conducted experiments to test the fatigue properties of exposed and unexposed rods. The goal of these experiments is to compare how the unexposed and exposed rods react to being tested at 10% of their minimum breaking strength (MBS), which is about 87 lb-in, for 10 million cycles (the practical endurance limit) or to failure. The rods were tested on an RBF-200HT machine when running at 6% MBS, about 57 lb-in. The RBF-200HT is a rotating cyclic fatigue testing machine which applies a specified moment onto the center of the sample. Due to constraints on the machine, the 6% MBS corresponds to an applied moment of 57 in-lb, which is the highest applied moment the machine would allow. This machine mimics the natural forces applied in the ocean, and 60-70 million cycles simulates a five second wave period for 10 years. Testing to 10 million cycles aims to find the endurance limit, or the stress level below which an infinite number of loading cycles can be applied to a material without causing fatigue. Before running the rod at 6% of its MBS, we tested one of the unexposed rods in a lower strength machine, the RBF-40HT, which ran at 3% MBS, about 26 lb-in. The unexposed rod went through this machine for 10 million cycles and did not break, which was expected due to the small moment applied. Prior to being tested in the machine, the rods were trimmed down to 10-inch sections. The samples were coated with epoxy using molds which we designed and had 3D-printed to fit our rod. Once the epoxy was cured after 48 hours, it was machined down to have a smooth, perfectly cylindrical finish. This allowed for the rod to fit evenly into the collets of the RBF machines and focused the stress onto the center of the sample, rather than causing stress concentrations at the collets.

2.2 Terminations

To connect the end of the composite rods to the anchor of the mooring system, a "termination" needed to be designed. Since rebar has never been used for aquaculture, the terminations were made custom for this purpose. The concept acts as a crimping mechanism in which two aluminum plates are bolted together, compressing the rebar in between. A diagram of the part is shown below in *figure 3*.

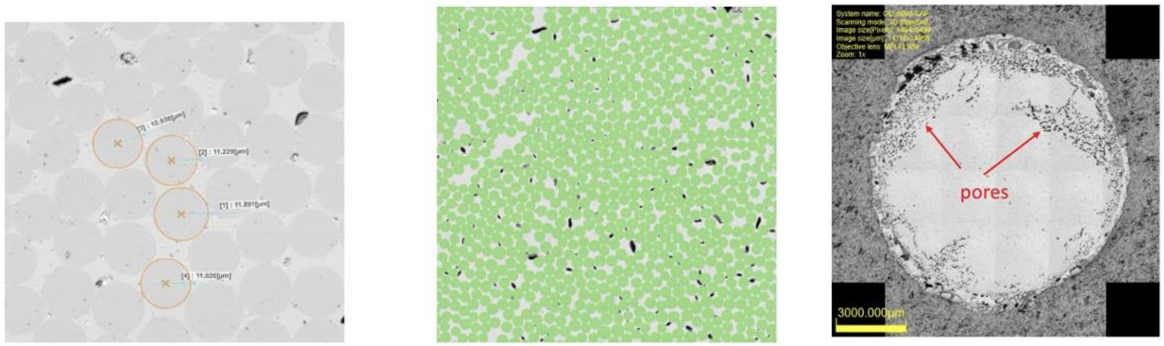
Figure 3: Composite termination concept design

As shown above, the hole in between the two plates is where the rebar rests, and has the same diameter as the rebar. Eight bolts are also placed to put an equal level of compression onto the rod. The larger hole can fit a shackle, which is connected to the anchor of the mooring system. The bolts are made of stainless steel isolated by plastic washers to prevent the stainless steel from making contact with the plates, and the plates are made of aluminum.

2.3 Microscopic Analysis of Composite Lines following a Nine Month Field Deployment

Six TUF-BAR composite lines were attached to the AquaFort in Portsmouth Harbor, seeded with sugar kelp, and left alone from December 2019 to October 2020. Cross-sections of these lines were cut and analyzed using a microscope; both unexposed and exposed samples were observed. Observations of the unexposed rods yielded fundamental characteristics, such as fiber diameter, fiber to resin ratio, and void space to matrix ratio. As identified in *figure 4*, the radius of the fiberglass fibers is 11 µm. The area fraction of the fibers was also determined to be 71.6%, which means that most of the other 29.4% of area is represented by resin. Pore locations tend to be towards the outside of the rod, so the ratio of pores to fibers is localized.

Following the analysis, signs of damage were shown on the exposed rods. Individual fibers towards the outer edges of the rods were degraded, and holes had started to form in between fibers. It is possible that these rods are not completely waterproof and small amounts of water trickle in over time. Since these rods were deployed in the winter, water could have expanded as it warmed with the summer months approaching, increasing the spaces between fibers. Hints of green were also seen in some of these holes, giving evidence of biofouling within the rod. It is unclear if this damage compromises the structural integrity of the rod, and further testing is needed to estimate the lifespan of these rods.



Radius of fibers ~ 11 um | Area fraction of fibers = 71.6% | Pore Locations on the Sample

Figure 4: Physical properties of unexposed rods

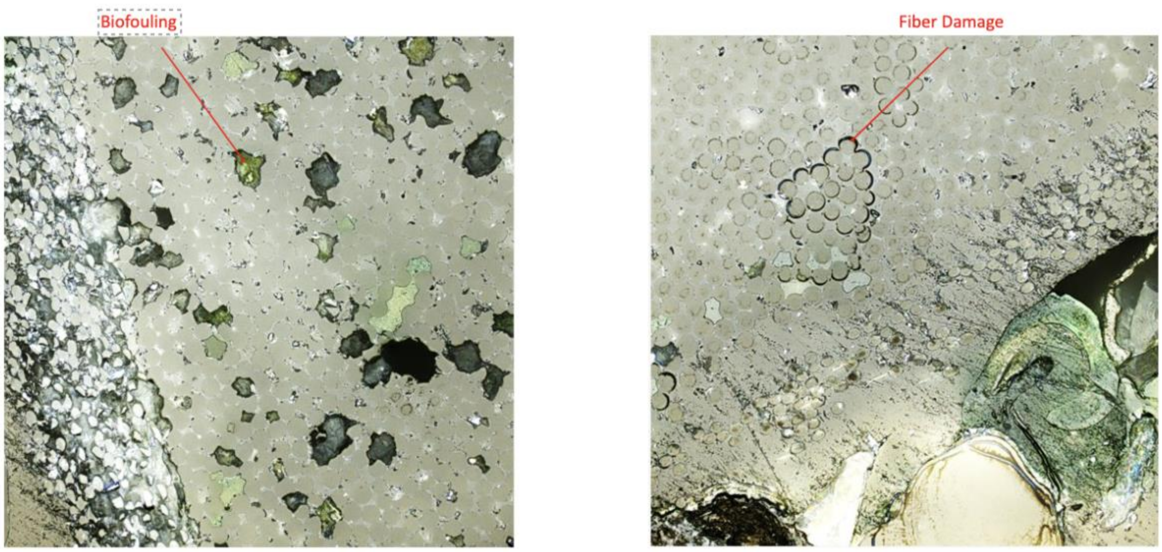


Figure 5: Evidence of damage to exposed rods

3. Results

Several experiments were conducted in our time working on this project. We have tested the tension strength of the composite line terminations, the fatigue life of the composite material itself, the amount of biofouling and species discovered growing on the composites between line types, and the presence and strength of kelp holdfast attachments. The results of the numerous experiments were promising, but more tests must be done in the future, including continued fatigue testing and holdfast attachment strength on different line types.

3.1 Testing of Composite Line Terminations

The composite line terminations are designed to withstand the natural forces of the ocean. A termination is composed of two aluminum plates, which are bolted together with the end of the composite rod inside. The bolts are torque wrenched to a force of 200 in-lb. During tension testing, a target goal of 4000 lbf was identified. This goal was achieved, and failure occurred at 6500 lbf, confirming the design was applicable to the intended field deployment.

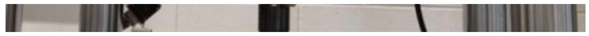


Figure 6: Intron test of composite terminations

A subsequent test was conducted at the Coastal Marine Lab pier in New Castle, New Hampshire. Terminations were attached to composite lines of 10 ft, 25 ft, and 75 ft in length. Each pair was put in tension to a force of 1300 lb. There were no signs of failure and the lines were deployed.

3.2 Fatigue Testing

An unexposed rod was tested in the lower capacity RBF-40HT machine. The rod ran for 10 million cycles at 3% of its MBS and did not break or crack in any way. Even though this did not help us determine the breaking strength of the rod, it showed us that the rod can at least withstand a moment of 26 in-lb. Since we did not get any new knowledge of the breaking strength of the rod, we decided to test an exposed rod in the higher capacity machine, RBF-200HT. This rod is currently still in the machine and has undergone 3 million cycles at the time of writing. Once this rod has either failed or reached 10 million cycles, we will test more exposed and unexposed rods in the RBF-200HT, because with more data comes more reliability. We want to see exactly when the rod breaks so we can know what force will accomplish this and if the rods will survive in nature.

3.3 Biofouling Identification and Research

A test structure with 6 TUF-BAR composite lines of different diameters (nominal diameters of 10, 13, 15, 20, 22, and 25 mm) were placed attached to the Aqua Fort about a quarter mile offshore from the UNH Pier at the Judd Gregg Marine Research Complex. The test structure was deployed in the water for 6 months and removed in October 2021 by Zach Moscicki, Arron Jones, and Erich Berghahn. Once the structure was removed, pictures of the kelp growth and biofouling accumulation were taken. Biofouling is the accumulation of living organisms on artificial surfaces by adhesion, growth, and reproduction (Cao *et al*. 2010). This degradation can have major economic impacts, so the mitigation of biofouling or finding a material that can withstand it is crucial to cost effective aquaculture systems. There are two major categories of marine adhesion organisms; biofilms such as bacteria and diatoms, and macrofouling organisms such as algae, barnacles, polychaete worms, mussels, bryozoans, and seaweed (Cao *et al*. 2010). The process of biofouling occurs by biochemical reactions including: extracellular polymeric substance (EPS) secretion, movement and secondary adhesion of microorganisms, formation of the biofilm, adhesion of macrofoulers, and by physical reactions including electrostatic interaction and water flow, which leads to the formation of the biofilm (Cao *et al*. 2010). First, we learned that barnacles produce an adhesion to the surface they inhabit (Visch 2020). It is glue based which could not only negatively affect kelp growth by limiting space availability, but also potentially damage the surface they attach to. Experiments should be done on barnacle attachment to composite lines over time to learn about degradation that may occur to the composite material. A potential concern could be if the barnacles create damage to the composite material surface; this might allow water into the composite center, which could change the composition and efficacy. Another concerning biofouling organism that we found could be the skeleton shrimp, which are associated with man-made structures including aquaculture infrastructure. Detailed knowledge is still lacking, but due to their high abundance, they are a concern when it comes to outcompeting with kelp for space. Two 3x3" sections on the kelp were measured and the approximate number of biofouling organisms were recorded. The kelp and biofouling from each of the 6 composite lines was placed into a respective bag, labelled, and frozen. The samples were then taken back to Spaulding Lab where they were defrosted. Using various identification books and online resources, organisms which had been removed from the test structure and frozen were sorted through, identified, and recorded.

Research was also conducted on how biofouling species could affect the Tuf-Bar fiberglass rebar used in this project. Since Tuf-Bar has not been deployed for kelp aquaculture on a large scale, information was drawn from the effects of biofouling on other deployments of glass-reinforced plastic. For example, it was found that when hulls of ships and boats are made of glass-reinforced plastic, they are prone to attachment of biofouling organisms (Swain *et al*. 2011). Additionally, when biofouling becomes severe, it can damage this coating and the hull itself (Swain *et al*. 2011). Hard, inert, non-toxic coatings can be used for hulls and are generally either epoxies, polyesters or vinyl esters; some reinforced with glass flakes, which includes substances that make up the Tuf-Bar rebar. These coatings are known to protect the hull against corrosion, and routine cleaning keeps biofouling to a minimum (Swain *et al*. 2011). Additionally, these coatings are non-toxic and do not leach harmful chemicals into the water (Swain *et al.* 2011).

Figure 7: Image of biofouling accumulated on the composite line test structure

3.4 Kelp and Biofouling Growth Experiment

An experiment was deployed at the UNH pier to collect data on the differences in kelp growth and biofouling accumulation between the composite lines under investigation and ropes that are typically used in kelp aquaculture, polypropylene and nylon. Two 6-foot lengths of each line material were secured vertically into the water, where one of each was seeded with sugar kelp to ensure growth. The experiment was monitored by staff members at the UNH pier and data was collected by Haley and Emma biweekly. The data that was recorded consisted of kelp length and width from the two longest kelp blades on each line, biofouling present, pictures taken of the full lines and kelp holdfasts as well as GoPro videos while the lines were still underwater to record active biofouling as many species swim off the lines when they are retrieved from the water. The length and width data will show how efficiently kelp grows on the composite line compared to polypropylene and nylon. Tracking the kelp holdfast growth with pictures will show how well the holdfasts grow around the composite material. The experiment has been ongoing for 5 weeks and will continue until the end of the semester.

Figure 8: Comparing the kelp holdfast attachment at 4-week growth between polypropylene (left), composite (middle), and nylon (right)

Figure 9: Comparing kelp holdfast attachment at 7-week growth between polypropylene (left), composite (middle), and nylon (right)

Figure 10: Mobile resident species (*Idotea phosphorea)* on the composite line

3.5 Holdfast Attachment Strength Tests

A field experiment at the Saco Bay test structure was completed to investigate the holdfast attachment strength of the sugar kelp to the TUF-BAR composite line. The ability of the kelp's holdfast to attach to the composite line is critical in rough ocean conditions. Poor attachment could cause the kelp to break off and harvest yield to be lost. The holdfast attachment strength was tested by looping a thin polypropylene rope around the stipe of the kelp using a girth hitch, and then attaching that loop to a hanging scale. The scale and rope attached to the kelp stipe were pulled until the holdfast detached, and a reading was taken at that moment. Measurements for single holdfasts of kelp were taken as well as groups of holdfasts. Many of the holdfasts were intertwined with one another so we tested their collective strength by grouping them together with the same girth hitch method. For singular fronds of kelp, the length and width were recorded. For groups of fronds with intertwined holdfasts, the number of fronds, maximum length, maximum width, and average length were recorded (Section 4.2, Table 2). 9 holdfast attachment strength tests were done on one end of the test structure, and 9 more were completed at the west side of the structure.

Holdfast attachment strength tests done by UNH Judd Gregg Marine Research staff on kelp growing on fiber ropes nearshore have been included in Section 4.2, Table 3 as a comparison to the composite line. A similar method was used to complete these tests. The stipes of the kelp were tied in a knot and looped around a fish scale to measure the holdfast attachment strength. In this test, only one stipe was pulled at a time. It was noted that the kelp was not in good condition due to warm temperatures and biofouling with hydroids.

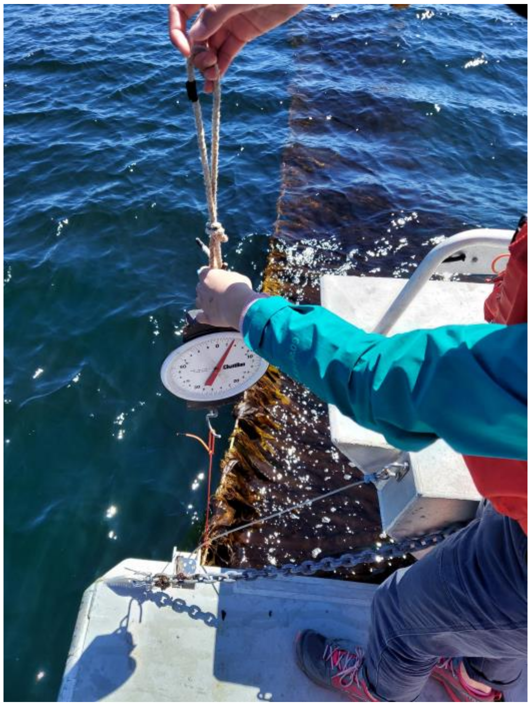


Figure 9. Holdfast attachment strength test set-up

Figure 10. Intertwined holdfasts from multiple fronds

4. Influence of Ocean Exposure

Future researchers will continue testing and observations on TUF-BAR composite lines to learn more about the ways in which ocean exposure affects these lines. Fatigue testing is ongoing and will continue until there is sufficient data to determine whether the lines will be able to survive in typical ocean conditions. Biological observations will also continue to see how effective composite lines are for kelp farming in regards to kelp holdfast attachments and susceptibility to biofouling.

4.1 Engineering

The results of the fatigue testing are still ongoing. This testing will continue on through the end of the semester and next year. So far, it was found that the unexposed rod can withstand a 26 in-lb moment (3% of the MBS) for 10 million cycles. As these fatigue tests carry on, we will gather more results, but at the time this paper was written we are only at 3.7 million cycles (and counting) for the exposed rod at a moment of 85 lb-in. Once a number of the exposed and unexposed rods are tested at 10% the MBS (87 lb-in), we will ideally have a better idea of when the rod breaks and if we need to increase the MBS to see this. This will also allow us to see how differently the exposed and unexposed rods react to this stress.

4.2 Biology Results

Our results showed that the same species were present on each line, regardless of diameter, but the abundance of each species each varied per line (Figure 11). A biofouling species that was not quantifiable was skeleton shrimp, so the abundance is not shown in Figure 4. Skeleton shrimp were completely covering all six lines and their abundance did not vary based on line diameter. Similarly, *Mytilus edulis,* or blue mussels, were very abundant as well, with between 200-400 per line. The other species present included various sea worms, barnacles, and isopods, as well as a small number of crabs, as seen in *figure 11*.

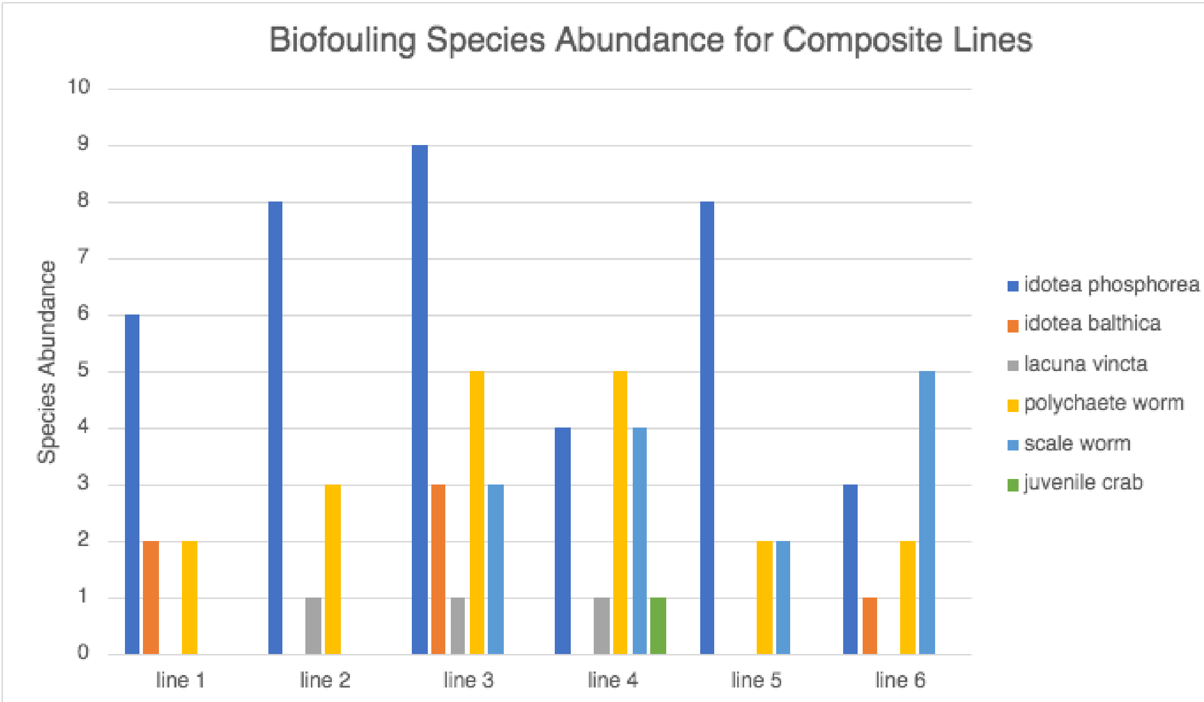


Figure 11: Graph comparing biofouling species abundances on 6 composite lines of different diameters (10, 13, 15, 20, 22, and 25 mm) retrieved from the UNH Aqua fort in October 2020.

From our experiment at the UNH pier, we saw that the sugar kelp was able to grow on the composite material at a comparable rate to the polypropylene and nylon ropes. Observations of biofouling on the three different line types were also similar. Kelp holdfast attachment is an important indicator of whether the composite material will be sufficient for kelp growth. The results of our 7-week deployment showed that kelp growth and holdfast attachment was similar across each line type, with nylon ropes having the shortest maximum kelp widths and lengths at the end of week 7, then the Tuf-Bar composite, and polypropylene having the longest maximum lengths and widths (Table 1). Kelp holdfasts also showed similar attachments and growth between line types throughout the experiment (Figure 8,9).

Our trip to the deployment site at Saco Bay in Maine gave us more information on how much weight the kelp holdfasts could withstand when attached to the Tuf-Bar composites. The results showed that a greater number of fronds increased holdfast attachment strength significantly (Table 2). For example, when the holdfasts were measured from 36 fronds together, the weight it could withstand before breaking was 25 lbs, compared to 1-5 lbs from only 1 frond (Table 2). The holdfast attachment strength of the kelp on the composite lines was lower compared to tests done on the fiber ropes. The average holdfast attachment strength of single pieces of kelp on the fiber ropes was 5.77 lbs while the average for the composite lines was 3.92 lbs. Although this is only a comparative study and the kelp from these two tests were in slightly different growth stages and conditions, these results indicate that the holdfasts are more effective at attaching to fiber ropes than the Tuf-bar lines.

Experiment Deployed on 03/17/2021			
	Line type	Width (inches)	Length (inches)
Week 2	Composite	1.5	31.5
4/2/2021		1.5	15.25
	Polypropylene	1.2	28.5
		1	29
	nylon	0.9	23
		1	15.5
Week 5	Composite	2.8	54.5
4/22/2021		2.5	22
	Polypropylene	2.1	25
		2.1	39.5
	Nylon	2.2	29.3
		1.6	22
Week 7	Composite	3.8	59.5
5/12/2021		3.1	35.5
	Polypropylene	3	60
		4	51
	Nylon	3.4	38.5
		2.8	43.5

Table 1: Comparative kelp width and length measurements between composite, polypropylene, and nylon lines

First Site			
max length (in)	max width (in)	holdfast attachment strength (lbs)	# of fronds
47.5	2.6	4	1
46.2	2.4	unattached	1
52.5	1.9	4	1
38	2	4.5	1
58	2.6	9	3
67	1.4	9	11
71	1.6	8	22
65.5	1.6	9	33
53.5	2.3	4	1

Second Site: West Side				
max length (in)	average length (in)	width (in)	holdfast attachment strength (lbs)	# of fronds
n/a	n/a	n/a	7	frond broke
61	47	2.8	25	36
41.5	n/a	1.8	2	1
64.5	n/a	2	5	1
45.5	n/a	2.5	4.5	1
75	55	3.6	17	36
57	46	1.8	12	39
37	not taken	1.8	6	2
60	not taken	2.4	11	6

Table 2: Kelp holdfast strength based on different numbers of fronds (kelp stipes) on TUF-BAR lines at two sites in Saco Bay, Maine on 05/12/2021.

Fiber Rope Kelp Holdfast Attachment Strength

	lbs.
1	5
2	9.5
3	4
4	4
5	10.6
6	3
7	3
8	8
9	5.4
10	5.2

Table 3: Kelp holdfast strength tests on fiber ropes tested at UNH Judd Gregg Marine Complex, done on 7/15/20

5. Conclusions

The overall goal for this project was to develop technology for composite lines to substitute regular mooring lines to minimize the risk of marine mammal entanglement. To do so, the performance of composite lines, including terminations and fatigue testing, was done in a laboratory setting. The lines were also tested in an offshore deployment. Additional goals were studying the effects on resins after offshore exposure and understanding whale entanglement mechanics.

So far, testing on both the biological and engineering fronts are leading to this goal. The terminations designed exceeded the requirement for tension and are currently in a test deployment in Saco Bay with line lengths of 10, 25, and 75 feet. Microscopic analysis of rod cross-sections showed possible damage to exposed rods that spent nine months in the water. Fatigue testing is currently being done on exposed rods to see if exposure to ocean conditions water has an effect on the material's useful lifespan. So far, conclusions cannot be drawn on this effect, and further research is needed.

TUF-BAR fiberglass rebar has never been used largescale in an ocean environment, so its behavior in seawater is still unknown from long term deployments. TUF-BAR is composed of vinyl ester resin and fiberglass, and based on our research, we can expect the fatigue life when exposed to seawater to be between 62-85% shorter than its dry fatigue life. From a literature review, the resin used in TUF-BAR, vinyl ester, was determined to be the preferred resin to use in marine environments compared to other resins because due to its chemical composition and durability.

From our field experiments, we observed that biofouling accumulation on all three-line types (polypropylene, nylon, and composite) is similar. From our research, we learned that the biofouling species take up space on the lines limiting growth, and the presence of biofouling can affect kelp growth due to space availability. Holdfast attachment to the surface of the composite is an important part of kelp growth and should be further investigated. From our trip to Saco Bay, we investigated how much tensile force the holdfasts could withstand while attached to the Tuf-Bar composites, but another useful experiment would be comparing kelp holdfast strengths when attached to nylon and polypropylene to the composite material consecutively throughout the growth stages to gain a better understanding of how the attachment strength varies between lines. We also found that as kelp grows, the holdfasts form complex attachments to each other and the line. When kelp is too small, the seeded line is necessary to keep the kelp attached because the holdfasts are too small to wrap around the line or other holdfasts, therefore the holdfast attachment strength is very low.

From our own research on the biofouling present on the lines, we were able to learn how these biofouling organisms could affect the composite material based on how they affect other, more commonly used materials. Although we can gauge how biofouling will affect the composite material on based on analogous examples of fiberglass performance in the marine environment (like in boat hulls), more research and deployment experiments using Tuf-Bar composites should be completed in order to gain a better understanding on how biofouling can affect the composite material long-term.

Overall, gaining a better understanding of how biofouling will affect the composite material, will allow us to see how the open ocean will affect our system. Laboratory tests can only tell us so much, so it is good to know what the rods will encounter while in seawater, surrounded by marine life. Composite lines for kelp aquaculture are an important technological advancement that could change the way aquaculture farms run. It provides a way to not disturb the natural environment while still successfully 'farming' kelp that can be later sold. It is crucial that as we advance technologically, we do not forfeit nature in the process. Combining engineering and biology helped us tackle this problem from two different angles. As this research continues on into the next year, more will be understood about how these rods will perform and we can better craft them to fit into the marine environment and last over the years.

6. References

1. Clement, D., Cawthron Institute, and Nelson. (2013), *Literature Review of Ecological Effects of Aquaculture.* Ministry for Primary Institutes, 4: 1-19.
2. Woodward, B.L., Winn, J.P., Moore, M.J. and Peterson, M.L. (2006). *Experimental modeling of large whale entanglement injuries.* Marine Mammal Science, 22: 299-310.
3. Howle, L.E., Kraus, S.D., Werner, T.B. and Nowacek, D.P. (2019), Simulation of the entanglement of a North Atlantic right whale (*Eubalaena glacialis*) with fixed fishing gear. Mar Mam Sci, 35: 760-778.

4. Knowlton, A.R., Robbins, J., Landry, S., McKenna, H.A., Kraus, S.D. and Werner, T.B. (2016), *Effects of fishing rope strength on the severity of large whale entanglements*. Conservation Biology, 30: 318-328.
5. Kraus, S., Fasick, J., Werner, T., & McFarron, P. (1970, January 01). [Pdf] enhancing the visibility of fishing ropes to reduce right whale entanglements: Semantic scholar.
6. Baldwin, K., & Byrne, J. (n.d.). (2012). Taut vertical line and North Atlantic right Whale FLIPPER.
7. Visch, W., Nylund, G.M. & Pavia, H. Growth and biofouling in kelp aquaculture (*Saccharina latissima*): the effect of location and wave exposure. *J Appl Phycol* **32,** 3199–3209 (2020). https://doi.org/10.1007/s10811-020-02201-5
8. Swain, G., Schultz, M., Candries, M., Ackx, G. (2011), *Ship Hull Coating Systems Simplified*. Hydrex nv. https://boudvanrompay.com/upload/author/files/d773e8c64281e311bbb75462b9ef5124.pdf
9. Cao S, Wang J D, Chen H S, et al. 2010. *Progress of marine biofouling and antifouling technologies*. Chinese Sci Bull, 2011, 56: 598–612, doi: 10.1007/s11434-010-4158-4

Appendix A

Summarizing Marine Mammal Entanglement

Emma Kross, Olivia Luthringer, Garrett Frohman

Aquaculture is an up-and-coming practice that could potentially reduce humans' effect on wild marine life and ecosystems. It is important to know exactly what you are implementing and how this will affect the environment it is in. Aquaculture lines can result in damage to marine animals, primarily whales, so our group is aiming to limit these interactions and ensure they do not result in death if they do happen. Factors such as line type, area implemented, and types of animals near the aquaculture system can affect how deadly these interactions are, or if they occur at all. As an example, New Zealand has only conducted small scale aquaculture projects, but they are doing a lot of research on how a potential large-scale system would affect the ecosystem it is in in their waters (Clement *et al.* 2013). Knowing the area, before you install anything will allow you to better know the impact that your system will have and you can better design it so its impact is minimal. Putting a system in the ocean without looking into what animals live there, what their niches are or how the animals interact together could be very detrimental to the lives of the wild animals and the farm animals.

Types of line

There are many different types of lines that can be used in aquaculture and they all have different effects on the wildlife in the area. The paper, "Experimental Modeling of Large Whale Entanglement Issues," investigated how different aquaculture lines can scratch a whale differently. Not all aquaculture lines are created equal, and all have their own pros and cons, so it is important to evaluate and test the most common ones. This paper looked at two separate lines-one made of polypropylene and the other made of a polyester/polypropylene mix. It is important to note that both lines were very flexible, so that when a whale did hit it this force was evenly dispersed and did not just impact one point. This allowed less damage to the whales and the lines. Neither of these lines were able to break the epidermis of the whales' tail, so it scratched the whale but its bending ability made it so the whales' injuries were very minor. The major reason that the line was so flexible was because it was composed of collagen fibers. The line composed of just polypropylene was stiff and composed of very defined fibers, which led to it leaving streaked marks on the whale. The line composed of both polyester and polypropylene had less defined fibers and less a more polished, smooth mark on the whale. Both types of lines caused about the same depth in their incision, but the mixture line's abrasion was longer than the just polypropylene line. The age of the rope also played a role on damage to the whale. For both lines, the older line was more abrasive and caused more damage due to its fraying fibers. Newer lines had all its fibers together, not poking out so this resulted in less cuts. So, when constructing an aquaculture line, it is important to factor in the age of the rope, what it is constructed of and what animals will be interacting with it (Woodward 2006).

Entanglement types/parameters that affect entanglement

There are three main types of entanglement that can occur when a whale encounters a fishing line or rope. The first is an entanglement involving a body wrap near the pectoral flippers (Howle 2019). Wraps are also common around the tail and mouth. Using a virtual whale entanglement simulator (VWES), it was found that several factors influenced whether a particular encounter would result in entanglement (Howle 2019). These factors are flipper sweep angle, roll direction, roll rate, current whale speed and direction relative to the path they're taking, the whale's vertical position in the water, and gear lateral offset (Howle 2019). It was found that if the line gets stuck at the forward insertion of the flipper, the entanglement would typically be a body wrap (Howle 2019). Other factors that influenced the likelihood of entanglement were the depth in the water column of encounter and the amount of tension (Howle 2019). It was found that the deeper the collision occurred in the water column, the more likely entanglement was (Howle 2019). It was noted that the evidence available does not indicate that increasing the stiffness of the line is a priority to prevent entanglements, and could potentially cause more severe injuries if this method is applied (Howle 2019).

There are multiple parameters to consider that affect entanglement including the color of the line, the diameter of the line, the line strength and tension. The first parameter that could affect entanglements is color. It has been found that changing the color of the line could reduce line encounters during the daytime. The hardest colors for whales to detect are white and green (Howle 2019), so these line colors should be avoided. Red and orange lines are the easiest for whales to detect from the furthest away (Howle 2019). Whales could detect red and orange lines from 3.85m to 4.1m away, black from 3.1m away, and green from only 1.9m away (Howle 2019). Trials showed that whales made more drastic maneuvers to avoid collisions when they can see the ropes in their path, but this isn't always the case (Howle 2019). It is important to note that this study was conducted in water with 8-10m of visibility. Better visibility could change how far the lines are noticed. A t-test showed that the difference in color was statistically significant.

The second parameter is line strength. It was found that right and humpback whales were found in ropes with significantly stronger breaking strengths at time of manufacture than minke whales (Knowlton 2016). Adult right whales were found in stronger ropes than juveniles, and then all humpback whale age classes (Knowlton 2016). The average rope breaking strength was 19.30kN (range 7.56-51.15kN) for right whales, 17.13kN (range 7.56-53.38kN) for humpback whales, and 10.47kN (range 2.89-17.81kN) for minke whales (Knowlton 2016). For right whales, severity of injuries increased since the mid 1980s, possibly due to changes in rope manufacturing in the mid 1990s that resulted in production of stronger ropes at the same diameter. The results from this study suggest that broad adoption of ropes with breaking strengths of 7.56kN (1700 lbsf) could reduce the number of life-threatening entanglements for large whales by at least 72%, and could provide sufficient strength to withstand the routine forces involved in many fishing operations (Knowlton 2016).

An experiment was conducted to determine the effects of an interaction between a NARW flipper and a taut rope. Although there is not much real-world data on this type of interaction, it was hypothesized that stiff lines reduce entanglement. The experiment had a model flipper (to scale), that was towed into high tension ropes. The interaction occurred at three angles of the leading edge of the flipper: acute, normal, and oblique (Baldwin 2012). With a max line tension of 325 lb, the interaction at the acute or normal zones of the flipper resulted in significant damage to the flipper, causing lacerations (Baldwin 2012). This paper could not confirm that tighter lines prevent entanglement, and more research is needed.

Table 1: Table showing the relevant parameters to consider that affect whale entanglement and their suggested use based on the papers from Howle *et al*., Knowlton *et al*., and Baldwin *et al*.

Parameter type:	Observations	Parameter suggestions:	Source:
Line Color	Red and orange lines can be detected by whales from 3.85m to 4.1m. Black line can be detected from 3.1m away, and green from only 1.9m away.	Use red and/or orange lines. Avoid white and green lines.	Howle *et al.* (2019)
Line Strength	The average rope breaking strength was 19.30kN (range 7.56-51.15kN) for right whales, 17.13kN (range 7.56-53.38kN) for humpback whales, and 10.47kN	Ropes with breaking strengths of 7.56kN (1700 lbsf) could reduce the number of life-threatening entanglements for large whales by at least 72%, and could	Howle *et al*. (2019)

	(range 2.89-17.81kN) for minke whales.	provide sufficient strength to withstand the routine forces involved in many fishing operations	
Tension/line stiffness	Tested flipper interaction with stiff rope at three angles. Two of three angles resulted in significant flipper damage. Max line tension tested was 325 lbs	More research needed. No suggestion given.	Baldwin *et al.* (2012)

Table 2: Showing the relative parameters of bending, tension, line age and site location, which all affect how an aquaculture system works and affects the wild marine life. This information is based on the papers Woodward *et al* and Clement *et al.*

Parameter type:	Observations:	Parameter Suggestion	Source:
Bending of rod	An aquaculture line that is able to bend, hurt the whale less as the force was equally distributed. The tightened end of the rod was able to bend by 1.6mm each cycle	Make sure your line is not completely stiff, as it will injure the whale or other animals more and it can still be strong when it bends.	Woodward *et al.* (2006)
Tension strength	Tension of 267N left an incision 0.31cm deep in the whale's tail (highest tension used)	No recommendation	Woodward *et al.* (2006)
Line age	Older lines cut the whales deeper than newer ones and had more fraying fringes	Make sure your line is new and not fraying, to reduce damage to the whales.	Woodward *et al.* (2006)
Aquaculture area	If you do not know the area you are implementing aquaculture technology, this could be damaging to the environment	Take note of the animals and life in the area and how they interact before you implement it, so you can try and have it fit in the ecosystem naturally	Clement *et al.* (2013)

References:

1. Clement, D., Cawthron Institute, and Nelson. (2013), *Literature Review of Ecological Effects of Aquaculture.* Ministry for Primary Institutes, 4: 1-19.
2. Woodward, B.L., Winn, J.P., Moore, M.J. and Peterson, M.L. (2006). *Experimental modeling of large whale entanglement injuries.* Marine Mammal Science, 22: 299-310.
3. Howle, L.E., Kraus, S.D., Werner, T.B. and Nowacek, D.P. (2019), Simulation of the entanglement of a North Atlantic right whale (*Eubalaena glacialis*) with fixed fishing gear. Mar Mam Sci, 35: 760-778.
4. Knowlton, A.R., Robbins, J., Landry, S., McKenna, H.A., Kraus, S.D. and Werner, T.B. (2016), *Effects of fishing rope strength on the severity of large whale entanglements*. Conservation Biology, 30: 318-328.
5. Kraus, S., Fasick, J., Werner, T., & McFarron, P. (1970, January 01). [Pdf] enhancing the visibility of fishing ropes to reduce right whale entanglements: Semantic scholar.
6. Baldwin, K., & Byrne, J. (n.d.). (2012). Taut vertical line and North Atlantic right Whale FLIPPER.

Appendix B

Summarizing Resin Research

Rachel Barden & Haley Fong

Tuf-Bar fiberglass rebar is a strong composite material composed of fiberglass and vinyl ester resin designed to withstand corrosive conditions and reinforce concrete structures. It has never been used in an ocean environment, so although it may be the perfect solution for constructing composite lines for kelp farming which will not cause marine animal entanglement, how it will behave in seawater is unknown.

Five papers have been useful in researching the strength and behavior of different types of resins and fibers in seawater. "Seawater Durability of Epoxy/Vinyl Ester Reinforced with Glass/Carbon Composites" by Murthy et al. describes the effects on the tensile strength, water uptake, flexural strength, and interlaminar shear strength of epoxy/fiberglass, vinyl ester/fiberglass, epoxy/carbon fiber, and vinyl ester/carbon fiber composites by exposure to seawater over a 450-day period. "Degradation in fatigue behavior of carbon fiber–vinyl ester-based composites due to sea environment" by Siriruk and Penumadu investigates the effects of seawater on the resin matrix due to cyclic loading, and confirms that the fatigue life of these composites is shortened by up to 85% when submerged in seawater compared to the fatigue life on dry land. "Fatigue life" in this context refers to the amount of time until the composite material experiences failure due to fatigue, measured in these studies in days. "Flexural Fatigue Life of Woven Carbon/Vinyl Ester Composites Under Sea Water Saturation" by Prabhakar et al. examines woven carbon fiber/vinyl ester composites and determines that under low strain the composites have comparable fatigue lives in dry and wet conditions, but under high strain the saturated composites have a significantly shorter fatigue life than the dry composites.

In the study by AM Visco et al., "Degradation effects in polyester and vinyl ester resins induced by accelerated aging in seawater," isophthalic polyester was compared to vinyl ester. Isophthalic polyester is a type of unsaturated polyester resin that is a thermoset, meaning that it can be cured from a liquid to solid under specific temperature conditions (netcomposites.com). It is the preferred polyester resin for marine applications. Vinyl ester resins are esters derived from vinyl alcohol and have a similar molecular structure to polyester but have fewer reactive ester sites (netcomposites.com-vinylester). The results of the degradation tests indicated that isophthalic polyester degraded more than vinyl ester due to its biphasic structure with low compactness that allowed for damage caused by the diffusion of seawater (Visco, 2012). DSC heat-flux curves, a system used for the calorimetric analysis of the residual enthalpy of curing, demonstrated two exothermic peaks for isophthalic polyester due to two separate cross-linking events. This biphasic structure is characterized by the main cross-linking of the polyester network followed by the formation polystyrene chains. The single peak in the vinyl ester DSC analysis demonstrates the vinyl ester monomers directly converting into a high molecular weight polymeric network with no polystyrene molecules creating additional free volume. (Visco, 2012) This compact network limits the amount of water gain in the material compared to isophthalic polyester. The compactness of the vinyl ester also attributed to higher chemical stability and greater resistance to hydrolytic reactions. After exposure to seawater, SEM micrograph images showed that compared to isophthalic polyester, vinyl ester had a more regular surface, no cavities or breaks, and uniform salt deposition. Color and consistency changes in the materials occurred during the immersion period, with both materials losing their transparency and changing color, indicating that physical and chemical changes occurred (Visco, 2012). Hardness measurements were also higher in vinyl ester. Isophthalic polyester is less expensive and can easily accommodate specifications by changing the chemical formula but is overall less resistant to degradation by marine environments than vinyl ester due to its chemical properties (Visco, 2012).

Vinyl ester and glass is a stronger combination than epoxy resin and glass; vinyl ester and carbon fiber is the strongest combination. From the paper titled “Seawater Durability of Epoxy/Vinyl Ester Reinforced with Glass/Carbon Composites” by Narasimha et al., “epoxy-based specimens showed a drop of 48% in flexural strength for an exposure time of 450 days, the same was 28% in the case of vinyl ester.” After a period of 90 days, "[v]inyl ester composites showed higher strength than the epoxy-based composites.” This research team also found that vinyl ester-based composites had a quicker time to reach stability in seawater than epoxy-based composites, with vinyl ester and carbon fiber reaching stability at 150 days, vinyl ester and glass reaching stability at 200 days, and epoxy/carbon as well as epoxy/glass reaching stability after 365 days. This means that epoxy-based composites are continuing to increase in water uptake for much longer than vinyl ester-based composites, which can be due to micro-cracks and delamination occurring within the resin matrix and the resin/matrix interface. Essentially, epoxy continues to break down and weaken longer than vinyl ester, and is weaker than vinyl ester. It is important to note that both epoxy resin and vinyl ester resin will perform better in dry conditions but will perform comparably at a lower strain in seawater, while they will have a significantly shorter fatigue life in seawater compared to dry conditions if under high strain.

Environmentally friendly alternative composites are still being researched for marine applications, but the research article by Peter Davies, “Environmental degradation of composites for marine structures: new materials and applications” suggests bio-sourced thermoplastic, acrylic resins, natural fiber-reinforced composites, and carbon fiber composites for potential use. Bio-sourced thermoplastics like polylactic acid (from corn) have an environmentally friendly source, but require high temperatures to cure and degrade quickly at moderate temperatures. Acrylic resins can be infused like vinyl ester to form thermoplastics which can be recycled, and results suggest that the sensitivity of acrylic thermoplastic matrix to seawater is lower than that of epoxy. Studies done on natural fiber composites using flax demonstrate that it could be justified to replace glass reinforcement. Dried flax fibers are extremely brittle but can absorb 40% by weight so they must be protected by the matrix to limit water absorption. Carbon fiber composites in tidal turbines have been tested, with the severe marine environment causing many failures in prototypes. Cyclic tests on these carbon fiber composite turbine blades indicated that short stitching showed very poor flexural fatigue and a compression failure mechanism. There is not extensive knowledge about these materials and their performance in the marine environment, but if toxicity is a major concern, one of these materials could potentially be used.

In designing an aquaculture structure that will break under the force of a whale impact, if a stronger composite than Tuf-Bar is needed to prevent breaking during normal ocean events such as strong currents or storms, a composite consisting of vinyl ester and carbon fiber will be stronger than the fiberglass rebar. However, these composites may also be too strong to break under the force of a whale impact; if this is the case, a composite using isophthalic polyester resin or epoxy resin with fiberglass would be weaker. The ideal composite material for this aquaculture structure must be able to withstand fatigue due to normal ocean events but weak enough to be snapped or broken by a whale impact.

Table 1: The table below gives the length of exposure, visual observations (microscopes-yes/no?), tests (fatigue, bending, etc.), and observations/conclusions (more/less reliable).

Source:	Length of exposure:	Visual observations (Y/N):	Tests performed:	Observations and conclusions:
Davies	365 days	No	Tensile strength, saturation weight gain, cyclic loading, flexural fatigue	
Murthy	450 days	Yes	Flexural strength, ILSS (calculated with flexural strength), tensile strength	Vinyl ester-based composites showed less water uptake and the drop in flexural strength, ILSS, and tensile properties is smaller for vinyl ester compared to epoxy-based composites
Prabhakar	140 days	Yes	Cyclic fatigue (using flexure), SEM scan	Fatigue life of saturated woven vinyl ester and carbon composites is ~62% less than dry, fatigue life greatly affected by strain range
Siriruk	Unknown	Yes	Fatigue (in-plane tensile cyclic loading)	Fatigue life of wet/immersed polymeric composites is

				85% shorter than dry
Visco	156 days	Yes	Water absorption, Calorimetric analysis, SEM, infrared spectroscopy, hardness, Izod resilience test	Chemical composition of vinyl ester is more compact and leads to less water uptake than isophthalic polyester resin

References:

1. Davies P. (2016). Environmental degradation of composites for marine structures: new materials and new applications. *Phil.Trans. R. Soc. A,* 1-12.
2. Murthy, H N & Sreejith, M. & Bangalore, Munishamaiah & Sharma, S. & Sheshadri, T.. (2009). Seawater Durability of Epoxy/Vinyl Ester Reinforced with Glass/Carbon Composites. Journal of Reinforced Plastics and Composites - J REINF PLAST COMPOSITE. 29. 1491-1499.
3. Prabhakar, Pavana & Garcia, Ricardo & Imam, Muhammad & Damodaran, Vinay. (2020). Flexural Fatigue Life of Woven Carbon/Vinyl Ester Composites Under Sea Water Saturation. International Journal of Fatigue. 137.
4. Siriruk, Akawut & Penumadu, Dayakar. (2014). Degradation in fatigue behavior of carbon fiber-vinyl ester based composites due to sea environment. Composites Part B Engineering. 61. 94-98.
5. Visco, Anna & Brancato, Vincenza & Campo, N. (2012). Degradation effects in polyester and vinyl ester resins induced by accelerated aging in seawater. Journal of Composite Materials. 46. 2025-2040.
6. Tuf-Bar. (2018, March 05). BAR: Fiberglass REBAR, ROCK BOLTS, form Ties & Anchors. Retrieved May 11, 2021, from https://www.tuf-bar.com/