Development of Synthetic Fiber-Reinforced Electro-Optical-Mechanical Cables for Use With Moored Buoy Observatories

Mark A. Grosenbaugh, Walter Paul, Dan Frye, and Norman Farr

***Abstract*—We consider an alternative to traditional high-modulus synthetic electro-optical-mechanical (EOM) mooring cables that are being used in single-point moorings for deep-ocean observatories. The alternative cable design is based on using low-modulus nylon or polyester fibers as the strength member. High-modulus EOM cables such as those that use Vectran fibers as the strength member are usually constructed with the conductors and optical fibers in the core and the strength member on the outside. The key aspect of the new design is that the strength member is placed in the center of the cable and the conductors and fibers are wrapped around the outside at a high helix angle to accommodate stretching of the center-strength-member. A comparison of the static and dynamic responses of moorings constructed with nylon, polyester, and Vectran EOM cables (for mooring scopes of 1.1 and 1.2 and deployment depths of 1800, 3000, and 5000 m) shows that the maximum total tensions of moorings made with nylon EOM cables are lowest under all conditions. Differences between the nylon and the Vectran EOM cable moorings are due principally to the differences in the dynamic tensions. Differences between the nylon and the polyester EOM cable moorings are due mainly to differences in static tensions caused by the higher specific gravity of polyester fibers. Reduction in the scope of all the moorings from 1.2 to 1.1 resulted in significantly higher tensions for the polyester and Vectran EOM cable moorings but only slightly higher tensions for the nylon EOM cable moorings.**

***Index Terms*—Electro-optical-mechanical (EOM) cable, moored ocean observatories, oceanographic moorings, surface moorings.**

I. Introduction

OVER the next decade, the National Science Foundation (NSF) plans to invest significant resources on the acquisition and construction of infrastructure for a network of ocean observatories as part of its Ocean Observatories Initiative (OOI) [1], [2]. Individual observatories will have different capabilities, but all will have the goal of providing scientists with the means to study oceanic and geological processes in real time. The OOI consists of three components: 1) a regional scale cabled observatory consisting of interconnected sites on the seafloor that are linked to shore by a fiber-optic communications cable; 2) an expanded network of coastal observatories; and 3) a global network of moored buoy observatories consisting of arrays of instruments connected by acoustical link or fiber optic cable to a surface buoy that transmits data ashore by satellite.

This paper is directed specifically at the needs of the moored buoy observatories [3]. One of the technical approaches planned for these moored systems is a single-point mooring that uses an electro-optical-mechanical (EOM) cable as its mooring line (Fig. 1). The cable maintains the connection between the anchor and the surface buoy. At the same time, it provides power and communication from the surface buoy to a benthic network of instruments through a set of copper conductors and optical fibers. Power is generated on the surface buoy and carried to the bottom by copper conductors. Data collected by a network of seafloor instruments are transmitted to the surface buoy through the optical fibers.

A critical component of the cable-linked single-point mooring is the EOM cable. Presently, it is difficult to find a cable design that meets the requirements demanded for this application. This was demonstrated recently when Monterey Bay Aquarium Research Institute (MBARI) deployed a commercially available EOM cable for use with their prototype observatory mooring (Fig. 1). Although the axial loading of the mooring was well below the breaking strength of the cable, the cable still failed due to "low-tension" bending [4].

The oceanographic community has extensive experience in the analysis and use of single-point surface moorings that are attached to the seafloor with elastically compliant nylon rope [5], [6]. However, the use of EOM cables for deep-ocean surface moorings is relatively new and presents significant challenges. EOM cables that are used for moorings need to have synthetic strength members that are lightweight to limit static and dynamic loads that act on relatively small surface buoys. Also, the design of an EOM cable for oceanographic moorings must combine copper conductors, optical fibers, and a synthetic strength member in such a way that the copper and optical elements stretch no more than 0.5% [7].

Most of today's synthetic fiber EOM cables are built with high elastic modulus fibers (e.g., Kevlar or Vectran) that limit the overall cable strain to less than 1% at typical working loads. Conductors and optical fibers can be further protected from overstraining through the use of a helix construction. By themselves, however, high-modulus EOM cables are unable to provide the compliance needed to accommodate ocean waves. The solution, in this case, is found in a mooring design that provides geometric compliance through extra mooring line length and extra elastic compliance through the incorporation

Manuscript received July 23, 2004; accepted August 24, 2005. This work was supported by the National Science Foundation under Grant OCE-0337893 and the Office of Naval Research (Ocean Engineering and Marine Systems) under Grants N00014-92-J-1269 and N00014-03-1-0008. **Associate Editor: R. C. Spindel**.

The authors are with Woods Hole Oceanographic Institution, Woods Hole, MA 02543 USA (e-mail: mgrosenbaugh@whoi.edu).

Digital Object Identifier 10.1109/JOE.2005.850937

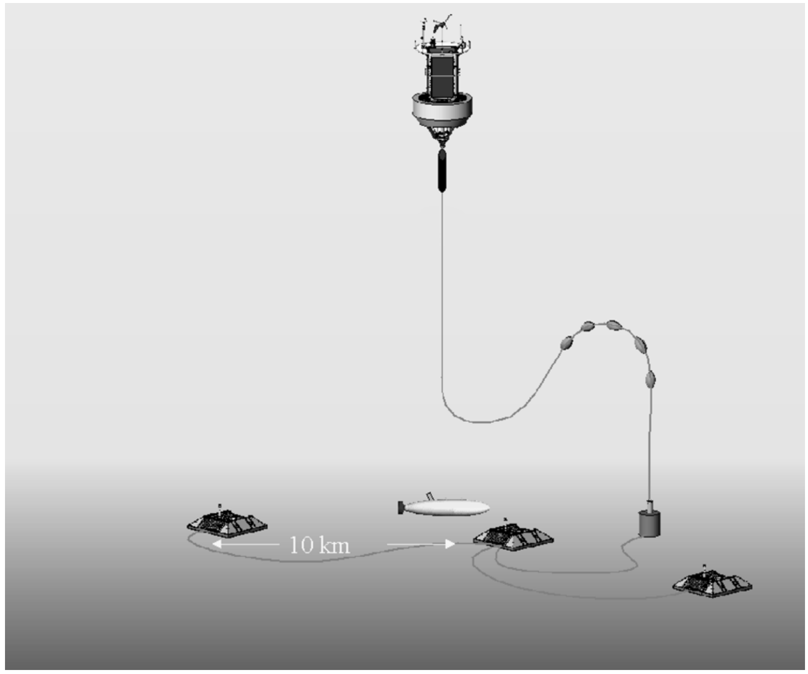


Fig. 1. Concept drawing of MBARI's inverse catenary ocean observatory mooring hardwired to benthic nodes [4].

Fig. 2. Snubber hose placed inline between a surface buoy and the top a Vectran EOM mooring cable to increase compliancy of the mooring and decrease dynamic tensions in waves.

at the top of the mooring of a special rubber hose section called a "snubber" (Fig. 2) that absorbs much of the wave motion [8]. A 16-m-long snubber was used by MBARI for their recent prototype mooring that also used a Kevlar EOM cable [4]. A second-generation mooring was recently deployed by MBARI that used a 24-m-long snubber with a Vectran EOM cable. Numerical studies of deep-ocean observatory moorings, which compared the performance of snubbers of different lengths placed in-line with a Vectran EOM cable, have shown the benefits of using longer snubbers, but only up to a maximum snubber length of about 70 m [9].

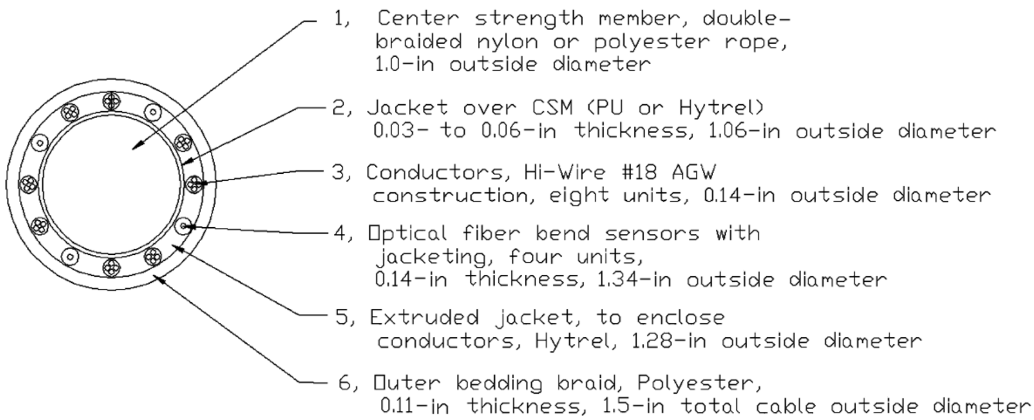
A new idea, which we present in this paper, is to use a material with a relatively low elastic modulus such as nylon or polyester as the cable's strength member. The strength member is placed in the center of the cable and optical fibers and copper conductors are wrapped around the outside of the strength member at a relatively high helix angle (all of which is covered with a protective jacket). The low-modulus synthetic strength members provide elastic compliance for handling wave dynamics (without the use of a snubber) while the high-angle helix pattern protects the fibers and conductors from overstraining.

We recently began the process of developing a reliable and cost-effective low-modulus synthetic EOM cable and mooring design (including the associated EOM cable termination and connection hardware) that could be used for cable-linked single-point moorings as part of a global network of moored ocean observatories. This development effort includes defining the specifications and developing the acceptance tests for an EOM cable, working with cable manufacturers to modify existing cable designs or create new ones, laboratory testing of samples to determine strength, bending, and fatigue characteristics, and a future full-scale field deployment to demonstrate the performance of the prototype cable system and compare it with the already-deployed MBARI mooring. In this paper, we review the designs for commercially available high-modulus EOM cables, describe our new design for a low-modulus EOM cable, and present the results from numerical calculations that compare the responses of moorings constructed with different types of synthetic fiber-reinforced EOM cables.

II. Synthetic EOM Cables

A. High-Modulus EOM Cables

The development of synthetic electromechanical cables began in the early 1970s shortly after the introduction of Kevlar fibers. Kevlar was the first high-performance fiber with strength and stretch characteristics similar to steel wire but with less than 10% of the wet-weight (i.e., weight in water). The low density of Kevlar cables made them attractive for mooring



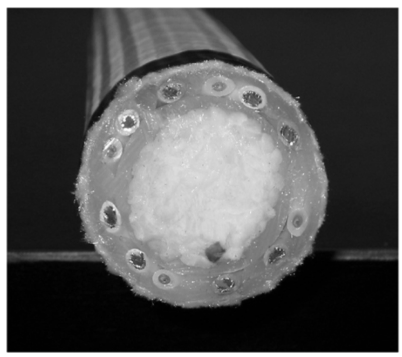


Fig. 3. Cross section of the nylon CSM EOM mooring cable.

applications because the amount of flotation that was needed to suspend the weight of the cable was dramatically reduced.

In the mid-1980s, new high-performance high-modulus fibers were introduced under the trade names Vectran, Spectra, and Dyneema. These fibers have similar strength and stretch characteristics as Kevlar but have higher abrasion resistance and higher resistance to cyclic loading. Spectra and Dyneema fibers by themselves have proved to be unsuitable for many marine cable designs due to excessive creep, which can occur under high sustained loads. More recently, a new commercially available fiber was introduced under the trade name Zylon. This fiber is almost twice as strong as Kevlar and Vectran and has similar stretch characteristics; however, its behavior in marine cables has yet to be investigated.

Most existing high-modulus synthetic EOM cables follow traditional designs of steel-armor EOM cables. Counter helical layers of high-modulus synthetic fibers cover a center core of electrical conductors and optical fibers. A protective plastic jacket is then extruded over the outside of the cable. Special metal or plastic tubes are used in the center core to protect the optical fibers during cable manufacturing and operational use. This overall cable constructions, which we term "center-conductor-core" (CCC), can be made to stretch less than 1% under maximum working loads. Copper wires and optical fibers at the center of the cable can be made to strain less than 0.5% with a proper choice of helix angle. A drawback of Kevlar CCC cables is that they are susceptible to kink-band formation when the Kevlar fibers are bent over a small radius, which can lower the breaking strength of the cable by up to 70% [10]. The Kevlar EOM cable that MBARI selected for their initial prototype test mooring failed during a severe storm. The failure was caused by localized bending fatigue and kink-band formation in the Kevlar layers near a series of clamp-on syntactic floats that had bunched together during the deployment [4]. When MBARI redeployed their ocean observing mooring, they replaced the Kevlar EOM cable with one made of Vectran. This new cable, which also uses a CCC construction, was chosen because it was shown, through testing, to be much improved in terms of bending fatigue.

B. Low-Modulus EOM Cables

Our design of a low-modulus synthetic EOM cable is based on a "center-strength-member" (CSM) construction with the core of the cable composed of a 25-mm diameter double-braided nylon or polyester rope. Wrapped around the outside of the rope are eight electrical conductors and four single-mode optical fibers that are imbedded in an extruded plastic covering. An outer jacket of braided polypropylene is used to improve handling and reduce wet-weight. A sketch and a picture of the cross section of a nylon EOM cable that uses a CSM construction are shown in Fig. 3. Analysis of the cable mechanics [11] shows that a CSM design with conductors spiraled at a proper helix angle provides long-term conductor durability by keeping the conductor stretch near zero. The oceanographic and offshore communities have a long history of using double-braided nylon [5], [6] and polyester ropes [12] in mooring applications, and their strength and fatigue properties are well known. In addition, double-braided nylon and polyester ropes are nearly torque

TABLE I
MATERIAL PROPERTIES OF THE DIFFERENT EOM MOORING CABLES AND THE SNUBBER HOSE, WHICH IS USED IN COMBINATION WITH THE VECTRAN EOM CABLE. VALUES IN PARENTHESIS CORRESPOND TO CABLES WITH FISHBITE PROTECTION. THE ELASTIC STIFFNESS OF THE NYLON CABLE AND THE SNUBBER HOSE IS APPROXIMATE BECAUSE THEY HAVE NONLINEAR STRESS–STRAIN CURVES THAT ARE USED IN THE ANALYSIS

Cable Properties	Nylon EOM Cable (CSM)	Polyester EOM Cable (CSM)	Vectran EOM Cable (CCC)	Snubber Hose
Elastic Stiffness EA (N)	$\sim 3.7 \times 10^5$	8.1×10^5	7.6×10^6	$\sim 3 \times 10^4$
Mass/Length (kg/m)	0.97 (1.33)	1.08 (1.47)	0.70 (1.17)	17.00
Wet-weight/Length (N/m)	0.95 (3.28)	2.28 (4.61)	0.64 (2.06)	21.96
Diameter (m)	0.039 (0.042)	0.039 (0.042)	0.028 (0.034)	0.1334
Normal Drag Coefficient	1.5	1.5	1.5	1.5
Tang. Drag Coefficient	0.01	0.01	0.01	0.01
Breaking Strength (N)	149 000	139 000	244 000	85 000

free due to the use of the same number and size of left-hand and right-hand spiraled rope strands in the construction. By applying the external conductor layer with a stretch-neutral helix angle [11], any significant rotation and torque by the conductors in a tensioned cable are avoided. The double-braided construction of the CSM also has the favorable property of a fairly high contraction of the diameter with increased tension. This allows the helix angle to be reduced in manufacturing, which helps lessen signal attenuation. These same considerations apply when considering core diameter changes due to hydrostatic pressure.

We terminate the low-modulus EOM cable with a standard eye splice applied to the CSM. The challenge in using this method is to pass the conductors and optical fibers safely around the termination hardware so that they are protected against external abrasion and not stressed by the tensioning and flexing of the cable. The termination is constructed by first unwinding the conductors and optical fibers from the end of the CSM. The rope strength member is then formed into an eye splice around a plastic thimble that is then attached to a large metal end fitting. A soft tapered polyurethane cover is then molded over the splice. The polyurethane section is then covered with a polypropylene bedding braid over which an additional polyurethane molding is applied. The bedding braid adds mechanical strength to the polyurethane boot. The conductors are then rewound over the polyurethane boot at the original wrap angle and are covered with a third layer of polyurethane for abrasion protection and to maintain the geometry. The termination section is finally covered with a braided polypropylene jacket. The ends of the optical fibers and electrical conductors are terminated with a bulkhead connector that is part of the metal end fitting. We successfully pull-tested the termination of a nylon EOM cable to 70 000 N, which is over two times the maximum predicted mooring line tension (as shown later in this paper) and was the maximum tension that could be achieved with our test apparatus.

The estimated properties of the proposed nylon and polyester EOM cables along with the properties of the Vectran EOM cable used by MBARI are listed in Table I. The diameter of the Vectran EOM cable is relatively small because of the high strength-to-volume ratio of the Vectran fibers. The breaking strength of the nylon EOM cable is higher than that of the polyester EOM cable due to the choice of the supplier for the CSMs (i.e., the chosen 25-mm double-braided nylon rope was stronger than an equal-diameter double-braided polyester rope). Values listed in the table in parentheses are for cables with fishbite protection, which in this case takes the form of stainless steel wires braided or imbedded into the outer covering of the cable. Mass per unit length, wet-weight per unit length, and cable diameter all increase due to the application of fishbite protection. Fishbite protection is typically used in the upper 700 to 1500 m of the mooring, depending on the deployment site [13].

III. MOORING DESIGN AND ANALYSIS

In this section, we analyze single-point deep-ocean observatory moorings that use either nylon, polyester, or Vectran EOM cables. We show the results of calculations of the responses of the moorings to environmental forcing (winds, currents, and waves) as a function of which type of EOM cable was used. A hypothetical deployment site in a water depth of 3000 m was initially chosen for the analysis. Later in the paper, we present results for the mooring response in shallower (1800 m) and deeper (5000 m) water depths.

All of the mooring systems are based on an "inverse catenary" single-point mooring configuration (Fig. 1). In an inverse catenary design, the mooring line length is typically 1.1 to 1.25 times the water depth to accommodate steady and low-frequency forcing from winds and currents. For this analysis, we calculate the responses for scopes of 1.1 and 1.2 (scope is defined as the ratio of the mooring line length to the water depth). Floatation is attached near the seafloor to prevent excess mooring line from touching the sea bottom when currents are slack. Under these conditions, the mooring line forms an S-shaped or inverse catenary loop. However, the loop is stretched out in all but the most benign conditions. The inverse catenary loop is constructed in the lower portion of the mooring so that the upper portion is float-free for use of a profiling instrument that can crawl up and down the mooring line. A snubber hose is shown in Fig. 1 for use with a Vectran EOM cable. The snubber hose provides the elastic compliance that is needed to accommodate high-frequency wave loading. The moorings that use nylon or polyester EOM cables do not need a snubber hose at the top because of their much lower elastic stiffness. Instead, beneath the surface buoy, a universal joint is installed through which electrical and optical cables are passed to a 6-m-long molded chain assembly (made with a 19-mm chain with an inner hose that acts as a mandrel for the conductors and an outer hose that protects the assembly). The bottom of the molded chain is connected directly to the top of the EOM cable with the electrical connections protected within the molded chain assembly. A 3600-m length of the EOM cable is then used for the 3000-m water depth to produce a scope of 1.2. (Later, the cable will be shortened to 3300 m to produce a scope of 1.1.) The top 700 m of the EOM cable is protected from fishbite. The inverse catenary shape is formed using a series of small syntactic floats attached to the cable 200 to 450 m above the bottom end, depending on which EOM cable is used. More are needed for polyester cables and less for nylon and Vectran EOM cables due their lower wet-weights (Table I). The floats have about 33 N of net buoyancy each and weigh about 50 N in air. At the bottom of the EOM cable, the conductors are connected to a molded chain similar to the one at the top of the mooring. The lower molded chain has a large float with about 500 N of net buoyancy at the upper end to keep the chain off the bottom in slack currents. For the Vectran EOM cable mooring, a 24-m-long snubber hose replaces the top 24 m of the mooring line (i.e., it replaces 6 m of molded chain and 18 m of fishbite-protected EOM cable). The effect of using different snubber hose lengths is investigated later in this paper. A complete listing of the components of moorings of scope 1.2 is given in the Appendix.

In the numerical analysis, we use attached cable floats for comparison purposes. The actual low-modulus CSM EOM cable that we will deploy will not have attached floats but will use an outer jacket of Cortland Industries' (Cortland, NY) proprietary low-density syntactic material to cover the lower 500 m of the EOM cable to produce the inverse catenary shape. While this construction increases the diameter of the lower cable section to 53 mm, it eliminates problems with slippage of attached floats due to any hydrostatic or dynamic changes in the cable diameter.

The static and dynamic responses of the mooring configurations were obtained using a Woods Hole Oceanographic Institution (WHOI) cable, a general-purpose numerical code for calculating the static and dynamic responses of moored and towed oceanographic systems [14]. The finite difference time domain simulation is built around a mathematical model of cable dynamics. The cable model is fully three-dimensional and includes the effects of torsion, bending, and geometric and material nonlinearities. For this application, the code was used in two dimensions to analyze the statics due to wind and currents and the dynamics due to the passage of ocean waves. For wave calculations, the program assumes that the vertical displacement of the surface buoy follows the wave elevation, which is described by a modified Pierson–Moskowitz spectrum.

For the analysis, a hypothetical mooring site in the North Pacific Ocean near the Juan de Fuca mid-oceanic ridge was chosen. A 25-year return period storm was defined with wind speed of 26 m/s, a significant wave height of 14.0 m, and a peak wave period of 21 s. A storm current profile was defined such that the current decreased linearly from 1 m/s at the surface to 0.5 m/s at 200 m and then decreased further to 0.1 m/s at the sea bottom (3000 m).

A. EOM Cable Mooring Response

The response of the mooring will be reported in terms of different tensions. The static tension, which is due to only wind and currents, is reported along the length of the mooring. The mean tension, the maximum dynamic tension, and the maximum total tension are reported at the anchor and at the surface buoy. The mean tension is the static tension plus the constant component of the wave forces (wave drift forces). The maximum dynamic tension is a statistical quantity and is defined as four times the standard deviation of the dynamic response. The maximum total tension is the sum of the mean and maximum dynamic tensions. We also report cable strain, and in this case the maximum strain is defined as the mean strain plus four times the standard deviation of the dynamic strain.

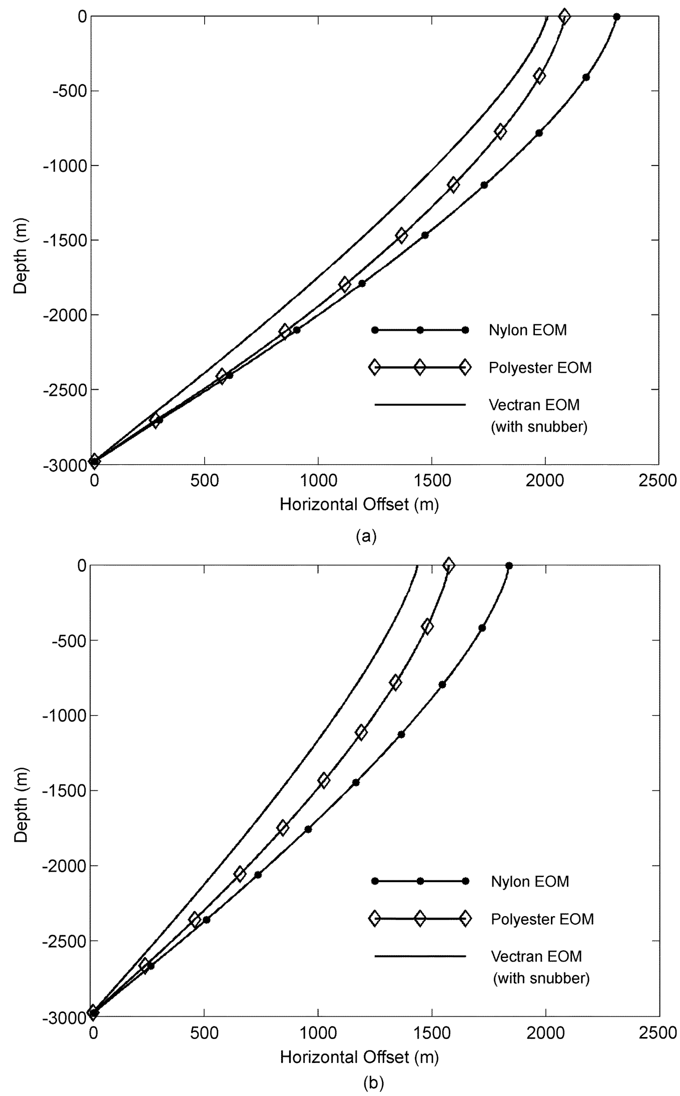


Fig. 4. Static configuration of different EOM cable moorings in a water depth of 3000 m due to 25-year storm winds and currents for scopes (a) 1.2 and (b) 1.1.

The static results for scope 1.2 indicated that the horizontal offset depended significantly on the elastic stiffness, EA, of the EOM cable. The elastic stiffness of the EOM cable determined how much the mooring scope increased due to stretch of the mooring line. The largest horizontal offset corresponded to the nylon EOM cable while the smallest offset corresponded to the mooring with the Vectran EOM cable and snubber [Fig. 4(a)]. The nylon EOM cable mooring stretched over 224 m under

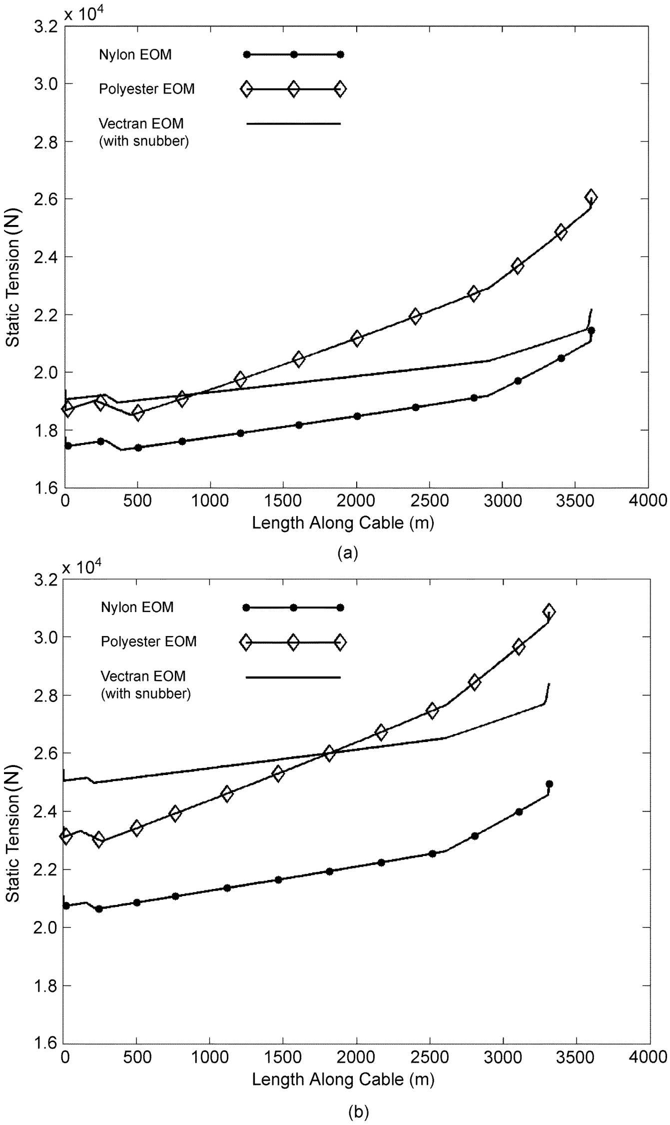


Fig. 5. Static tension along the mooring line for moorings using different types of EOM cable in a water depth of 3000 m due to 25-year storm winds and currents for scopes (a) 1.2 and (b) 1.1. The anchor is located at 0 m.

these forcing conditions while the Vectran/snubber system only stretched 22 m. Most of the stretch in the Vectran EOM cable mooring was taken up by the snubber, which stretched over 53% of its length (∼12.8 m of stretch). The catenary shape of each mooring also depended on the wet-weight of the mooring line. The increased angle of the polyester EOM cable mooring near the surface, in particular, was due to the higher specific gravity of the polyester EOM cable.

The static tensions, which were calculated using just the wind and current forcing (no waves), were a function of the wet-weight, elastic stiffness, and the drag of the mooring cable. For scope 1.2, the highest static tensions corresponded to the polyester EOM cable mooring [Fig. 5(a)]. This was due mainly to the high wet-weight of the mooring line, which affected the rate of increase of the static tension from the anchor to the surface [i.e., the slope of the static tension curve in Fig. 5(a)]. The static anchor tension of the Vectran EOM cable mooring, for scope 1.2, was approximately equal to that of the polyester EOM cable mooring because of the higher elastic stiffness of the Vectran EOM cable even though the overall stiffness of the mooring line was modulated by the low elastic stiffness of the snubber. Also, while the low wet-weight of the Vectran EOM cable helped to decrease the static tension at the surface buoy, it acted to increase the static tension at the anchor. This was because the mooring line angle at the anchor was steeper due to the lower wet-weight of the cable, and the static tension at the anchor increased to overcome the horizontal drag over the length of the mooring line. The static anchor tensions for the nylon EOM cable mooring were the lowest due principally to its lower elastic stiffness. However, for scope 1.2, the extra wet-weight of the nylon EOM cable compared to that of the Vectran EOM cable caused the static tension at the surface buoy of the nylon EOM cable mooring to be nearly identical to that of the Vectran EOM cable mooring [Fig. 5(a)].

Calculations of the dynamic response, for scope 1.2, in a severe sea state showed the lowpass filter and damping characteristics of moorings constructed with either nylon or polyester EOM cable compared to a mooring constructed with a Vectran EOM cable and a snubber hose (Fig. 6). Because of this, the dynamic tension at the anchor of the nylon and polyester EOM cable moorings was significantly reduced from the dynamic tension at the surface buoy (Table II). The dynamic tension at the anchor of the Vectran EOM cable mooring was actually increased compared to the dynamic tension at the surface buoy. While the snubber accommodated the wave motion and helped lower dynamic tension at the buoy, it was not successful at damping the motion because of its short length. The nylon EOM cable mooring had the lowest maximum dynamic and total tensions at both the anchor and the surface buoy (Table II). The polyester EOM cable mooring had lower maximum dynamic tensions and lower maximum total anchor tensions than the Vectran EOM cable mooring. However, the maximum total tensions at the surface buoy of the polyester EOM cable mooring were highest overall because of the high static tension at the top of the mooring [Fig. 5(a)]. The maximum total tensions at the surface buoy of the Vectran EOM cable mooring were nearly as high as those of the polyester EOM cable mooring because of the higher maximum dynamic tensions and an increase in the mean tension of 1000 N due to wave drift forces on the snubber.

B. Effect of Mooring Scope

We examined the effect of mooring scope by shortening the EOM cables of each mooring by 300 m and repeating the analysis. This gave a total EOM cable length of 3300 m and a mooring scope of about 1.1.

The horizontal offset of each mooring was reduced from that of the mooring with scope 1.2 (Fig. 4). The curves for the static tension (due to wind and current only) shifted upward due to the decrease in scope (Fig. 5), with the largest shift occurring for the Vectran EOM cable mooring due to its much higher overall elastic stiffness. The increase in static tension in all three moorings due to the shallower catenary shapes and the accompanying decrease in geometric compliancy was balanced by a reduction in the wet-weight of the entire mooring cable due to the shortening of each cable by 300 m. This was especially true for the polyester EOM cable mooring, which has a significantly higher

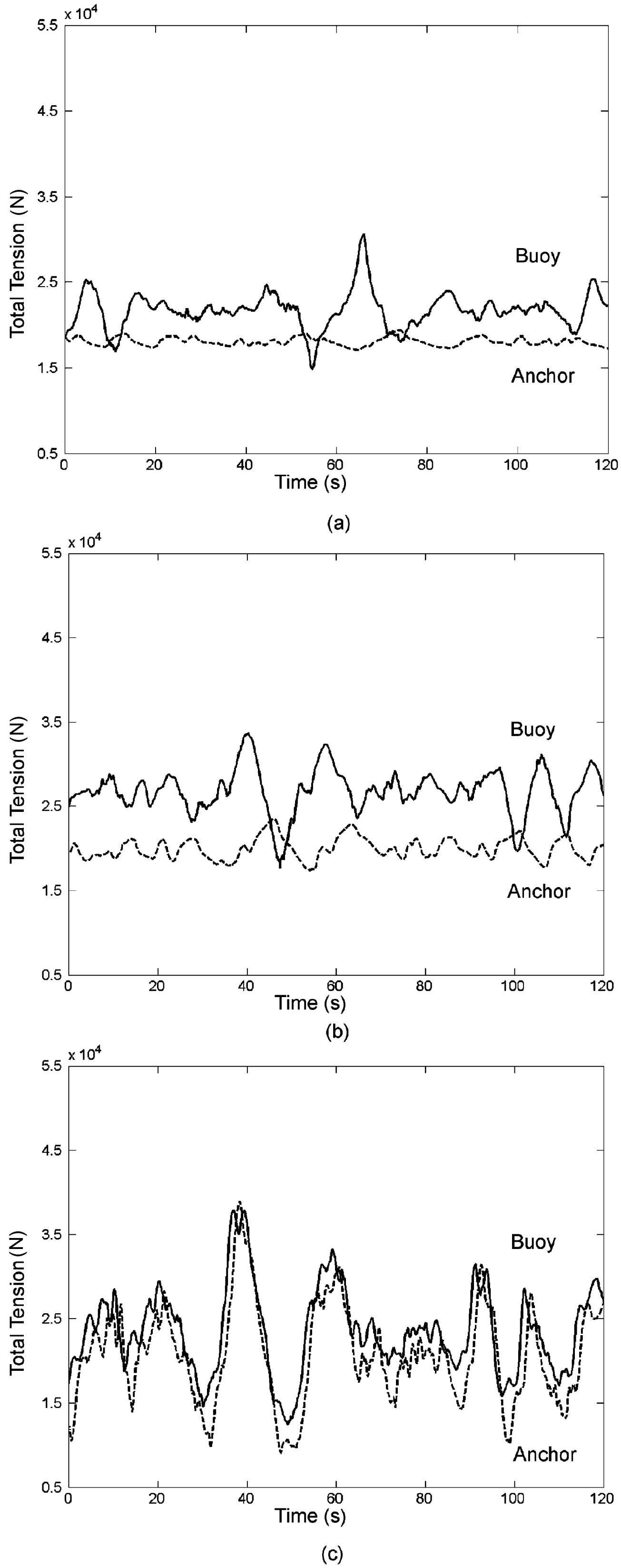


Fig. 6. Time series of the total tensions at the surface buoy and anchor of a mooring made up of (a) nylon EOM cable, (b) polyester EOM cable, and (c) Vectran EOM cable plus snubber hose in a water depth of 3000 m due to 25-year storm winds, currents, and waves. The scope of the moorings is 1.2.

specific gravity than the other EOM cables. The mean tensions (which include wave drift forces as well as wind and current) for the nylon, polyester, and Vectran EOM cable moorings increased by 13, 18, and 25%, respectively, at the surface buoy and 15, 21, and 27%, respectively, at the anchor (Table II).

The maximum dynamic tension at the surface buoy was reduced for the nylon EOM cable mooring, was nearly unchanged for the polyester EOM cable mooring, and was increased for the Vectran EOM cable mooring. The higher maximum dynamic tension for the nylon EOM cable mooring with scope 1.2 was due to the presence of a natural period of about 21 s in the mooring system, which coincided with the peak period of the input spectrum. The increase in maximum dynamic tension for the Vectran EOM cable mooring was most likely due to the nonlinear load elongation behavior of the snubber hose (i.e., the elastic stiffness of the snubber increases with mean tension). The maximum dynamic tension at the anchor was nearly invariant to changes in scope for both the nylon and the polyester EOM cable moorings. The maximum dynamic tension at the anchor increased for the Vectran EOM cable mooring, which is consistent with the increase in dynamic tension at the surface buoy and the all-pass filter characteristics of the Vectran/snubber setup (Fig. 6).

The maximum total tensions at the surface buoy for the nylon, polyester, and Vectran EOM cable moorings increased by 5, 13, and 18%, respectively, due to the reduction in mooring scope (Table II). In absolute terms, the increase in maximum total tension was 1500 N for the nylon EOM cable mooring, 4700 N for the polyester EOM cable mooring, and 7800 N for the Vectran EOM cable mooring. The maximum total tension at the anchor increased by 15, 17, and 18% for the nylon, polyester, and Vectran EOM cable moorings (Table II).

C. *Effect of Deployment Depth*

The response of EOM cable moorings with scope 1.2 deployed in a 1800- and 5000-m water depth was calculated by adjusting the length of the EOM cable and modifying the lower portion of the current profile. The current profiles all began with a current of 1.0 m/s at the sea surface, which decreased to 0.5 m/s at a depth of 200 m. The profiles then decreased at different rates but all becoming equal to 0.1 m/s at the respective sea bottoms (at 1800 and 5000 m).

The mean, maximum dynamic, and maximum total tensions for moorings deployed in 1800 and 5000 m are given in Table III. The maximum total tensions of moorings deployed in 1800, 3000, and 5000 m for 25-year storm winds, currents, and waves are plotted in Fig. 7. The top panel of Fig. 7 gives the maximum total tensions at the surface buoy, and the bottom panel gives the maximum total tensions at the anchor. For the low-modulus nylon and polyester EOM cable moorings, the maximum total tension increased with deployment depth. This was due to an increase in mean tension caused by the extra weight and drag of the longer mooring line. The maximum dynamic tensions at the anchor of the nylon and polyester EOM cable moorings decreased with depth due to an increase in damping. However, the decrease in maximum dynamic tension was not large enough to offset the changes in mean tension. Overall, the maximum dynamic tensions at the surface buoy increased with deployment depth for the nylon and polyester EOM cable moorings due to the extra mass of EOM cable that

TABLE II

SUMMARY OF RESPONSE OF MOORINGS MADE FROM DIFFERENT TYPES OF EOM CABLES IN 25-YEAR STORM CONDITIONS FOR A DEPTH OF 3000 m. THE MEAN TENSION INCLUDES THE EFFECTS OF WIND, CURRENT, AND WAVES. MAXIMUM DYNAMIC TENSION IS DEFINED AS FOUR TIMES THE STANDARD DEVIATION OF THE DYNAMIC RESPONSE. THE MAXIMUM TOTAL TENSION IS THE SUM OF THE MEAN AND MAXIMUM DYNAMIC TENSIONS. MAXIMUM STRAIN IS DEFINED AS THE MEAN STRAIN PLUS FOUR TIMES THE STANDARD DEVIATION OF THE DYNAMIC STRAIN. THE FIRST NUMBER OF EACH ENTRY CORRESPONDS TO SCOPE 1.2. THE NUMBER IN PARENTHESES CORRESPONDS TO SCOPE 1.1

	Nylon EOM Cable Scope = 1.2 (1.1)	Polyester EOM Cable Scope = 1.2 (1.1)	Vectran EOM Cable Scope = 1.2 (1.1)
MEAN TENSION			
Surface Buoy	21600 N (24500 N)	26600 N (31500 N)	23200 N (29000 N)
Anchor	18100 N (20800 N)	20000 N (24100 N)	20400 N (26000 N)
MAXIMUM DYNAMIC TENSION			
Surface Buoy	8400 N (6900 N)	10600 N (10400 N)	20500 N (22500 N)
Anchor	1900 N (2100 N)	5100 N (5300 N)	23100 N (25300 N)
MAXIMUM TOTAL TENSION			
Surface Buoy	30000 N (31500 N)	37200 N (41900 N)	43700 N (51500 N)
Anchor	20000 N (22900 N)	25100 N (29400 N)	43500 N (51300 N)
MAXIMUM CABLE STRAIN			
Top (below snubber)	0.091 (0.094)	0.045 (0.050)	0.006 (0.007)
Anchor	0.067 (0.075)	0.031 (0.036)	0.006 (0.007)
MAXIMUM SNUBBER STRAIN			
Surface Buoy	—	—	0.692 (0.718)

TABLE III

SUMMARY OF RESPONSE OF MOORINGS MADE FROM DIFFERENT TYPES OF EOM CABLES IN 25-YEAR STORM WINDS, CURRENTS, AND WAVES FOR DEPTHS OF 1800 AND 5000 m. THE SCOPE OF THE MOORINGS IS 1.2. SEE TABLE II CAPTION FOR DEFINITIONS

	Nylon EOM Cable Depth = 1800 m (5000 m)	Polyester EOM Cable Depth = 1800 m (5000 m)	Vectran EOM Cable Depth = 1800 m (5000 m)
MEAN TENSION			
Surface Buoy	16500 N (28700 N)	20800 N (36800 N)	20200 N (29700 N)
Anchor	14000 N (23500 N)	15800 N (25000 N)	17900 N (25500 N)
MAXIMUM DYNAMIC TENSION			
Surface Buoy	6700 N (7400 N)	8100 N (11300 N)	30000 N (16100 N)
Anchor	2500 N (1300 N)	6600 N (2900 N)	31900 N (15900 N)
MAXIMUM TOTAL TENSION			
Surface Buoy	23200 N (36100 N)	28900 N (48100 N)	50200 N (45800 N)
Anchor	16500 N (24800 N)	22400 N (27900 N)	49800 N (41400 N)
MAXIMUM CABLE STRAIN			
Top (below snubber)	0.072 (0.103)	0.033 (0.058)	0.006 (0.006)
Anchor	0.056 (0.080)	0.027 (0.034)	0.006 (0.006)
MAXIMUM SNUBBER STRAIN			
Surface Buoy	—	—	0.719 (0.664)

had to be accelerated up and down by the surface buoy when it moved in waves. However, the maximum dynamic tension at the surface buoy for the nylon EOM cable mooring as a function of water depth was more variable because its response, as already noted in the previous subsection, was affected by the presence of natural periods in the mooring transfer function, which itself depends on mooring line length.

The maximum total tension for the Vectran EOM cable mooring decreased as the deployment depth was increased from 1800 to 3000 m. After which the maximum total tension was essentially constant. The mean tension of the Vectran EOM cable mooring increased significantly with increased deployment depth, similar to that seen for the nylon and polyester EOM cable moorings. However, the maximum dynamic tension of the Vectran EOM cable mooring decreased significantly as the Vectran EOM cable became longer. Thus, at greater deployment depths, the increase in mean tension was offset by the decrease in maximum dynamic tension.

D. *Effect of Snubber Length*

Lastly, we examined the effect of snubber length on the response of the Vectran EOM cable mooring to show that the length of snubber hose was not a significant variable in the comparison between low-modulus EOM cables and high-modulus EOM cables. We used a mooring with scope 1.2 in a water depth of 3000 m and varied the length of the snubber hose while keeping the total length of the mooring line constant (i.e., if the snubber was increased by 1 m, the length of the EOM cable was reduced by 1 m). The results are shown in Fig. 8. As the length of the snubber increased, there was a tradeoff between the extra weight of the hose, which acted to increase the mean tension, and the reduced elastic stiffness of the system, which acted

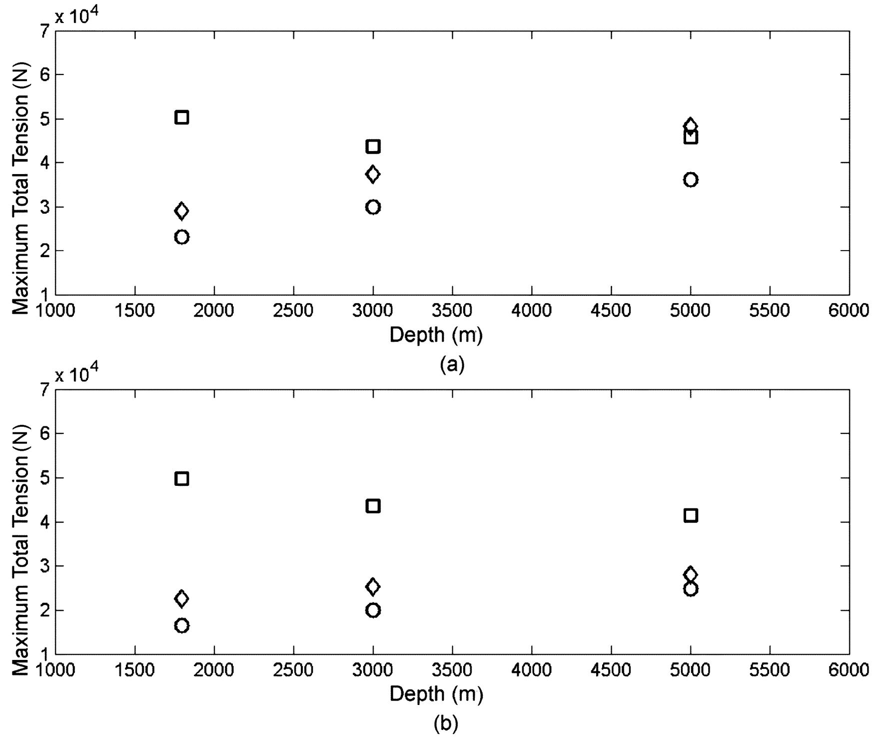


Fig. 7. Maximum total tension of moorings made with different EOM cables in 25-year storm winds, currents, and waves as a function of deployment depth. The moorings have a scope of 1.2. Values are taken from Tables II and III. Symbols are defined as: □ Vectran EOM cable mooring, ◊ polyester EOM cable mooring, and ○ nylon EOM cable mooring. (a) Surface buoy. (b) Anchor.

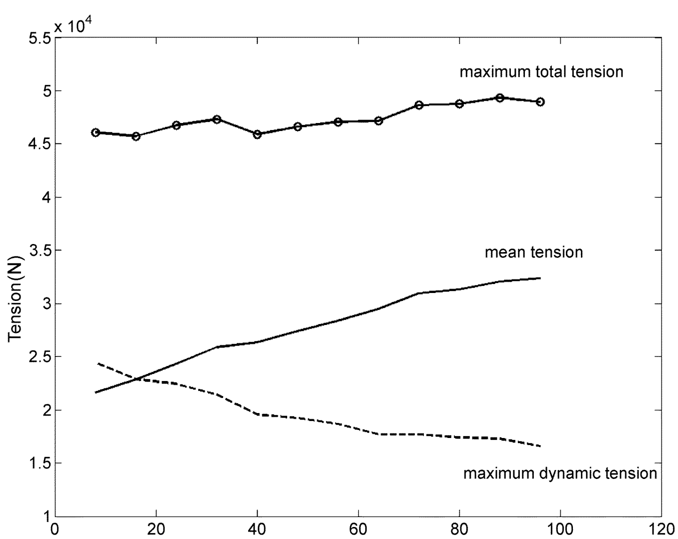


Fig. 8. Mean tension, maximum dynamic tension, and maximum total tension of the Vectran EOM cable mooring in a water depth of 3000 m due to 25-year storm winds, currents, and waves are plotted as a function of the length of the snubber hose. The scope of the mooring is 1.2 in all cases.

to lower dynamic tension. The result was that the maximum total tension was nearly unchanged for snubber hose lengths that were less than 70 m. Similar results were found by [9].

IV. Discussion and Conclusion

The results of this study showed that a single-point deep-ocean mooring constructed with a low-modulus EOM cable had a number of advantages over mooring systems that were based on high-modulus EOM cables. In particular, the mean, dynamic, and total tensions were low over the length of a mooring constructed with a nylon CSM EOM cable when compared with a mooring constructed with a Vectran CCC EOM cable (with a snubber hose). Moorings made with polyester CSM EOM cables, whose elastic modulus was twice that of nylon EOM cables but still an order of magnitude less than the Vectran EOM cable, had high mean tensions at the surface buoy due to the specific gravity of the polyester strength member. However, low dynamic tensions along the length of the polyester EOM cable mooring helped produce, in most cases, lower total tensions than the Vectran EOM cable mooring. An exception was found for the 5000-m deployment depth where the maximum total tension at the surface buoy for the polyester EOM cable mooring was slightly higher than that for the Vectran EOM cable mooring, though the anchor tension was still much less.

The lower maximum total tensions that were calculated at the bottom of the nylon and polyester EOM cable moorings will allow for the use of lighter anchors to hold the moorings in place, and the lower dynamic tensions over the length of the mooring, which are inferred from the calculated dynamic tensions at the anchor and surface buoy, will cause a reduction in the cyclic fatigue of the cable and other mooring components. Also, the use of nylon and polyester EOM cables will lead to the elimination of the snubber hose, which is cumbersome to handle during deployment and has a bending concentration at its base.

Reducing the scope of the moorings from 1.2 to 1.1 caused the maximum total tension to increase no matter which EOM

TABLE IV
COMPONENTS USED IN CALCULATIONS FOR MOORINGS WITH SCOPE 1.2 DEPLOYED IN A 3000-m WATER DEPTH. FOR SCOPE 1.1, THE EOM CABLE JUST BELOW THE FISHBITE SECTION IS SHORTENED BY 300 m

Mooring Component	Nylon EOM Cable Mooring (m)	Polyester EOM Cable Mooring (m)	Vectran EOM Cable Mooring (m)
Surface Buoy	Discus Buoy	Discus Buoy	Discus Buoy
19-mm Chain (Replaced With Snubber for Vectran EOM Cable Mooring)	6	6	24
EOM Cable With Fishbite Protection	700	700	682
EOM Cable	2520	2450	2545
EOM Cable With 33 N Net Buoyancy Floats Spaced Equally 5 m Apart	100	240	75
EOM Cable	280	210	280
19-mm Chain With 500 N Net Buoyancy Syntactic Float at the Top	6	6	6
Anchor	—	—	—

cable was used. The increase was most pronounced in the Vectran EOM cable mooring. The change in the maximum total tension of the nylon EOM cable mooring in a 3000-m water depth (Table II) was small and indicated that a smaller scope mooring could be used in this case without sacrificing static or dynamic performance.

The maximum total tensions for the low-modulus EOM cable moorings (both nylon and polyester) increased with deployment depth due to an increase in the mean tensions. Conversely, the total tensions for the Vectran EOM cable mooring decreased due to a decrease in the dynamic tensions (Table III). In fact, the maximum total tension at the surface buoy of the Vectran EOM cable mooring in a 5000-m water depth was slightly less than that of the polyester EOM cable mooring, though it was still much greater than that of the nylon EOM cable mooring. The maximum total tensions at the anchor of the nylon and polyester EOM cable moorings were always much less than those of the Vectran EOM cable mooring. This was because of the low dynamic tensions at the anchor of the low-modulus EOM cable moorings caused by the lowpass filter and damping characteristics of the mooring system (Fig. 6).

High-modulus Vectran EOM cables that use a CCC construction are still attractive because of the low overall cable strain at maximum working loads, which makes it easier to minimize strain of the copper conductors and optical fibers. Also, mature termination technology exists for CCC cables, while the termination methods described in this paper for CSM cables are just now being developed.

APPENDIX

Please see Table IV.

ACKNOWLEDGMENT

The authors would like to thank D. Bentley of Cortland Cable Company for his input in the design and construction of the nylon and polyester EOM cables.

REFERENCES

[1] National Research Council, *Illuminating the Hidden Planet: The Future of Seafloor Observatory Science*. Washington, DC: Nat. Acad. Sci., 2000.
[2] A. R. Isern and H. L. Clark, "The ocean observatories initiative: A continued presence for interactive ocean research," *Mar. Technol. Soc. J.*, vol. 37, no. 3, pp. 26–41, 2003.
[3] R. Detrick, D. Frye, J. Collins, J. Gobat, M. Grosenbaugh, R. Petit, A. Plueddeman, K. von der Heydt, B. Wooding, J. Orcutt, J. Berger, R. Harriss, F. Vernon, J. Halkyard, and E. Horton, *DEOS Moored Buoy Observatory Design Study*. Arlington, VA: National Science Foundation/Ocean Sciences Division, 2000.
[4] J. A. Hamilton, M. Chaffey, E. Mellinger, J. Erickson, and L. McBride, "Dynamic modeling and actual performance of the MOOS test mooring," in *Proc. OCEANS*, San Diego, CA, 2003, pp. 2574–2581.
[5] H. O. Berteaux, *Buoy Engineering*. New York: Wiley, 1976.
[6] M. A. Grosenbaugh, "Designing oceanographic surface moorings to withstand fatigue," *J. Atmos. Ocean. Technol.*, vol. 12, no. 5, pp. 1101–1110, 1995.
[7] W. Paul, D. Bentley, M. Chaffey, and D. Frye, "Electrical and electro-optical mooring links for buoy based observatories," in *Proc. Scientific Submarine Cable Workshop*, Tokyo, Japan, 2003, pp. 201–206.
[8] W. Paul, A. Bocconcelli, and M. Grosenbaugh, "Drifting buoy systems using elastic rubber stretch hoses," in *Proc. Boss Behavior Offshore Structures*, Cambridge, MA, 1994, vol. 2, pp. 213–225.
[9] S. Han and M. A. Grosenbaugh, "On the design of single-point cable-linked moorings for ocean observatories," *IEEE J. Ocean. Eng.*, vol. 31, no. 3, pp. 585–598, Jul 2006.
[10] P. G. Riewald, R. G. Walden, A. S. Whitehill, and A. S. Koralek, "Design and deployment parameters affecting the survivability of stranded aramid fiber ropes in the marine environment," in *Proc. OCEANS*, Washington, DC, 1986, pp. 284–293.
[11] W. Paul, "Design considerations for stretch conductors in oceanographic moorings" Woods Hole Oceanogr. Inst., Woods Hole, MA, Tech. Rep. WHOI-95-15, 1995.
[12] A. C. Fernandes, C. J. M. DelVecchio, and G. A. V. Castro, "Mechanical properties of polyester mooring cables," *Int. J. Offshore Polar Eng.*, vol. 9, no. 3, pp. 208–213, 1999.
[13] H. O. Berteaux and B. Prindle, "Deep sea moorings fishbite handbook" Woods Hole Oceanogr. Inst., Woods Hole, MA, Tech. Rep. WHOI-87-8, 1987.
[14] J. I. Gobat and M. A. Grosenbaugh, "Time-domain numerical simulation of ocean cable structures," *Ocean Eng.*, vol. 33, pp. 1373–1400, 2006.

Mark A. Grosenbaugh received the B.S. and M.S. degrees from Stanford University, Stanford, CA, in 1976 and 1983, respectively, and the Ph.D. degree from the University of California, Berkeley, in 1987.

He joined the scientific staff at Woods Hole Oceanographic Institution, Woods Hole, MA, in 1987 and is currently an Associate Scientist in the Department of Applied Ocean Physics and Engineering. His research interests include dynamics of moored and towed oceanographic cable systems.

Walter Paul received the M.S. degree in mechanical engineering and economics from the University of Darmstadt, Darmstadt, Germany and the Ph.D. degree in mechanical engineering from the University of Hannover, Hannover, Germany.

He is currently a Senior Engineer at the Woods Hole Oceanographic Institution, Woods Hole, MA. His specialty is the design and application of fiber ropes, electromechanical and electro-optical-mechanical cables, and fiber reinforced rubber hoses to oceanographic moorings.

Dan Frye (M'90) received the M.S. degree in physical oceanography from Oregon State University, Corvallis, in 1971.

He was a Staff Scientist at Argonne National Laboratory, Argonne, IL, from 1971 to 1974 and at EG&G Environmental Consultants, Waltham, MA, from 1974 to 1983. He was a Division Manager at Ferranti ORE, Falmouth, MA, from 1983 to 1987. He is currently a Senior Research Specialist at Applied Ocean Physics and Engineering Department, Woods Hole Oceanographic Institution, Woods Hole, MA. His research interests include ocean moorings, satellite telemetry, and ocean instrumentation.

Norman Farr received the B.S. degree in electrical engineering from University of Massachusetts, Lowell, in 1990.

He was a Senior Project Engineer at Fiberspar, Inc., from 1990 to 1993 and Principal Engineer and Manager at CardioFocus, Inc., from 1993 to 2003. He is currently at Woods Hole Oceanographic Institution, Woods Hole, MA, where he is a Senior Engineer in the Applied Ocean Physics and Engineering Department. He holds seven patents on laser and fiber optic techniques for medical instrumentation. His current research interests involve the application of optical techniques in the deep ocean.