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Advanced Mooring Lines for Marine Energy Workshop – Summary Report

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ABSTRACT

This report summarizes the outcomes of the virtual Advanced Mooring Lines for Marine Energy Workshop. The workshop convened experts from industry, academia, and national laboratories to identify key challenges associated with the deployment of synthetic mooring lines for marine energy applications. Discussions focused on four technical areas—materials, failure and degradation, testing, and modeling. Despite the significant promise of leveraging synthetic mooring systems for marine energy applications, discussion highlighted broader research and development needed to address the lack of validated long-term performance data, insufficient structural health monitoring frameworks, limited large-scale testing capabilities, and gaps in predictive modeling. Overall, the workshop emphasized the importance of coordinated research and development efforts to advance reliable, durable, and cost-effective synthetic mooring solutions for marine energy applications.

Acknowledgment

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Author Contributions

Author contributions following the CRediT system [1]. P.J.C.: Conceptualization, Data curation, Funding acquisition, Project administration, Resources, Visualization, Writing - original draft, and Writing - review & editing; B.A.H.S.: Conceptualization, Funding acquisition, Project administration, Resources, Writing - review & editing; B.G.: Resources, Writing - review & editing; P.M.: Resources, Writing - review & editing; G.B.: Resources, Writing - review & editing; D.M.: Writing - review & editing; F.P.M.: Writing - review & editing; C.S.: Conceptualization, Data curation, Resources, Writing - review & editing

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EXECUTIVE SUMMARY

The virtual Advanced Mooring Lines for Marine Energy Workshop convened experts from industry, academia, and national laboratories to identify critical challenges associated with deploying synthetic mooring lines for marine energy applications. Discussions spanned four technical areas: Materials, Failure and Degradation, Testing, and Modeling. Invited speakers for each technical area include Peter Davies from Ifremer, Mark Huntley from Whitehill Manufacturing, Budi Gunawan from Sandia National Laboratories, and Stein Housner from National Laboratory of the Rockies.

Participants agreed that while synthetic mooring solutions offer promise, the implementation of these materials lacks validated long-term performance data, robust structural health monitoring frameworks, scalable testing capabilities, and high-fidelity models. These technical gaps hinder confident deployment in marine environments characterized by extremely high cycle loading, biofouling, and abrasion.

Recommendations emphasized the need for standardized testing protocols, integration of smart sensing technologies, and development of digital twins to connect operational data with predictive models. Participants highlighted the urgency of collaborative research and development to close these technical gaps to ultimately ensure reliable and cost-effective mooring solutions for marine energy applications.

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1. INTRODUCTION

Marine energy technology is a key alternative source of energy to address the advancing national energy objective of becoming an energy exporter [2]. The nation's numerous coastlines and rivers offer the opportunity to harvest wave and tidal energy. It is estimated that the marine energy resource totals 2,300 TWh/yr, which is equivalent to approximately 57% of the electricity generated by all 50 states in 2019. Capturing just 10% of that potential resource is enough energy to power approximately 22 million homes [2].

To achieve this objective, however, marine energy technologies must demonstrate large-scale electricity production, reliable long-term deployments, and cost reduction compared to other energy resources [3]. To advance these technologies, the U.S. Department of Energy Hydropower and Hydrokinetic Office (H2O) provides critical funding for the research, development, and deployment of marine energy technologies [2]. These funding efforts seek to address the challenges associated with widespread deployment of marine energy technologies. One ongoing Foundational Research and Development (FR&D) activity of H2O is Advanced Materials and Manufacturing (AM&M). This FR&D activity seeks to identify and explore the potential of adopting new materials and processes to increase longevity, reduce costs, and improve energy capture [3]. The outcome of this activity aims to provide developers with the necessary materials science and engineering needed to overcome technological barriers and reliability uncertainties. Foundational understanding gained in material performance and reliability will ultimately enable developers to improve designs and shorten the time elapsed between design and open water testing. The primary materials of focus for this program include fiber reinforced composites (FRCs), FRCs interfaced with metals, and synthetic mooring line materials. Additionally, the team is focused on the corrosion and biofouling of these materials when deployed within representative environments.

To date, numerous organizations both domestically and internationally have focused on the key challenges associated with adopting these materials within marine energy technologies. To capture both industry and academia input on outstanding technical challenges and future direction, a workshop on materials and manufacturing R&D investments for wave and current energy technologies was conducted in October 2021, titled "WPTO Workshop on Materials & Manufacturing for Marine Energy Technologies." Outcomes from the workshop include R&D needs across a variety of areas, including testing, modeling, manufacturing, and material selection for wave energy converters (WEC) and current energy converters (CEC) [3]. The identified needs have helped H2O define a comprehensive strategy for integrating these materials and manufacturing efforts within marine energy technologies.

As R&D efforts progress, there are still a variety of challenges associated with integrating these materials. In particular, how these materials within WEC and CEC interact or interface with the mooring system is critical. Recent workshop findings have identified moorings as a critical component needing performance improvement in order to meet the needs for widespread deployment of marine energy technologies. In order to understand the underlying technological challenges facing both academic and industry partners specific to marine energy moorings, a workshop was conducted in December 2025 to invite members of the community to provide their input (see video recording: Synthetic Mooring Lines Workshop). The desired outcomes of the workshop include the following:

- Establish primary materials of interest to the community
- Establish primary materials limitations
- Establish candidate materials for testing/characterization
- Establish where modeling needs further development
- Leverage workshop results to guide future synthetic mooring line evaluation

The workshop was structured to support the desired outcomes by including presentations from community experts while also allowing time for open discussion of the challenges preventing widespread deployment of mooring solutions. The workshop was held virtually for three hours and forty-five minutes with about 250 registered participants, of which over 100 were in attendance. The high numbers reflect the community's strong interest in understanding the current research gaps affecting synthetic mooring line widespread deployment. The breakdown of those who registered is shown in Fig. 1-1 with participants from U.S. national laboratories, universities, and government agencies, as well as industry partners and participants in attendance from outside the U.S. The largest category consisted of participants from U.S. industries. Breaking down this category further, about 5% of companies were broadly classified as manufactures of ropes, belts, or moorings. About 35% were classified as marine energy developers and technology providers, and about 60% were companies from other sectors interested in learning more about synthetic mooring lines.

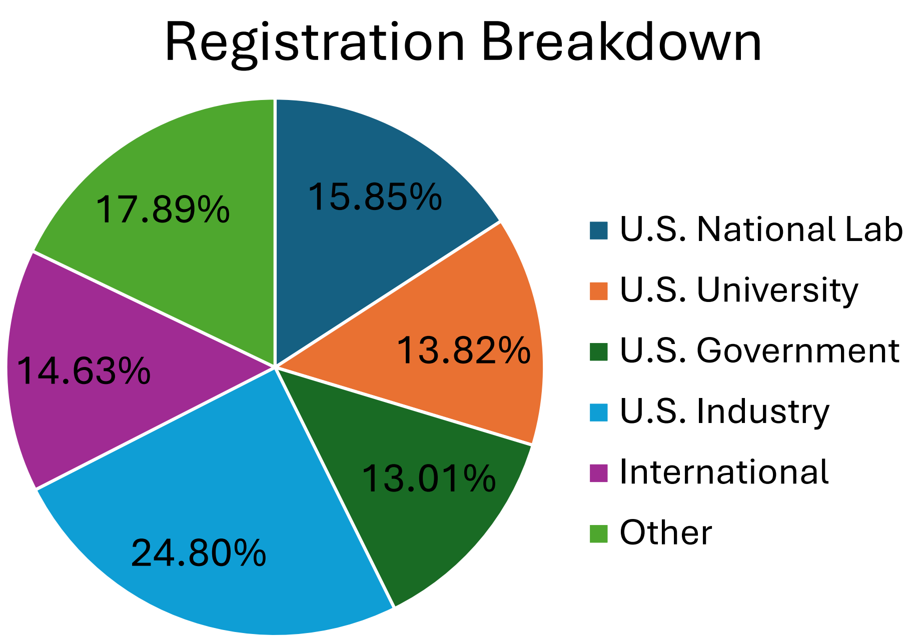

Figure 1-1. Breakdown of registered participants based on their affiliation.

The workshop had four primary target focus areas related to each design aspect of synthetic mooring lines within marine energy environments:

- Past, Present, and Future Materials
- Expected Failure Mechanisms, Environmental Degradation, and Health Monitoring
- Testing Facilities, Characterization Capabilities, and Standards
- Modeling Capabilities and Needs

Guest speakers were invited to give a plenary presentation for each research topic, which was followed by a breakout session with dedicated time for participants to answer free-response and polling questions. These questions and following discussions allowed participants the opportunity to provide their personal expertise and knowledge towards the state-of-the-art deployment of synthetic mooring lines while also helping identify key R&D research gaps and provide their input on future direction.

In what follows, we outline for each topic area 1) a presentation summary by the invited guest, 2) the breakout discussion question and free response/polling questions given to the participants, and 3) summary of key items, issues, and recommendations based on participant responses.

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2. PAST, PRESENT, AND FUTURE MATERIALS

2.1. Presentation

In the materials topic, a presentation was given by Peter Davies, who is a marine energy researcher for the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) in France. See page 38 for slides that were presented. Peter's talk covered a brief introduction on the history of various materials used for mooring lines, discussed the design criteria for material selection, highlighted several materials actively being investigated, discussed the environmental impact of material choice, and provided his perspective on the future direction and needs of synthetic mooring materials to become more commonplace.

For future direction, Peter identified the following as key focus areas:

- Generate more reliable fatigue data for polyamide and make the data available.
- Discover how we can benefit from the experience of mooring line deployments, including instrumentation and residual properties.
- Develop rope recycling methods, explore alternative material options, and perform life cycle analysis.

2.2. Breakout Session

The following questions were provided to the participants to answer either verbally or by typing in a response specific to materials for synthetic mooring applications. The first question in this list was presented standalone and was used as a key question to guide participant discussion, while the following questions were presented all at once for participants to answer at their own pace:

- Do we have the right off-the-shelf materials available to effectively deploy synthetic mooring lines for marine energy applications?
- Are you able to access domestic suppliers to acquire the materials you need for testing?
- What public data are available and lacking at various length scales (e.g., fiber data, braided data, component data)?
- Which materials have you previously used and are you most interested in utilizing moving forward?
- What are the limitations of existing materials in terms of cost, manufacturability, etc.?

- What mooring line designs are you most interested in exploring or further developing (e.g., braiding styles, hybrid materials/components)?
- What materials selections and/or differences do you consider for WEC and TEC moorings within marine freshwater and seawater environments?

In response to the first question, participants generally felt that currently available materials do not sufficiently meet the needs for synthetic mooring line deployment. While materials currently exist, there is great uncertainty in their performance metrics. The common sentiment was the need for improved instrumentation to improve data collection and additional validation data to fully characterize performance.

To summarize the findings from the remaining questions, several common themes and areas of concern were found. There is a general skepticism associated with the adequacy/accuracy of off-the-shelf materials for synthetic mooring line applications for marine energy. While some materials may suffice for initial deployments, most participants agreed that current options lack comprehensive data on long-term durability under cyclic loads, biofouling, and abrasion. It was mentioned that existing laboratory-scale measurements were inaccurate when compared to full-scale deployment and observations. In short, laboratory-scale experiments were deemed insufficient to replicate real-world conditions, which prompted the call for improved experiments supplemented with field deployments for validation. These real-world deployments would ideally incorporate periodic material performance inspections or smart detection/monitoring for rapid and continuous assessment with the goal of populating shareable datasets with the community.

Key materials of interest identified by the participants included rope manufacturing using high-modulus polyethylene, ultra-high molecular weight polyethylene (e.g., Spectra), polyester, nylon, aramid (e.g., Kevlar), and liquid crystal polymer (e.g., Vectran). Participants mentioned interest in manufacturing hybrid designs (i.e., two or more fiber types) to focus on abrasion resistance and reduce internal friction. For all materials, however, the impact on the environment in terms of recyclability was of great concern when discussing end-of-life strategies. Furthermore, key areas of concern for material deployment included biofouling, abrasion, seawater corrosion, long-term fatigue and creep durability, ultraviolet degradation, line termination and splicing, water absorption, and material costs.

3. EXPECTED FAILURE MECHANISMS, ENVIRONMENTAL DEGRADATION, AND HEALTH MONITORING

3.1. Presentation

The invited speaker to discuss expected failure mechanism and degradation was Mark Huntley from Whitehill Manufacturing Corporation, who is currently a senior engineer for rope applications and R&D with over 25 years of experience. See page 42 for slides that were presented. He presented the challenges associated with populating fatigue curve data tables and the accuracy and large uncertainty between laboratory-scale tests versus full-scale testing. A potentially large area of uncertainty in fatigue prediction with low amplitudes and high mean loads stems from the concept of mean load locking. As described by Mark, mean load locking occurs when rope constructions have minimal change in their geometry while in service, which results in minimal abrasion. The influence of mean load locking may explain why there is increased number of cycles until failure (i.e., increased endurance) compared to ropes that experience continuous abrasion. Mark also provided his perspective on future direction with a focus on low-amplitude fatigue performance, improved rope design to optimize fatigue, further investigation into the effects of mean load locking, and validation of fatigue properties and strength retention as a function of cycle number for nylon ropes at scale.

For future direction, Mark identified the following as key focus areas:

- Improve understanding of nylon fatigue performance at low amplitudes.
- Improve understanding of mean load locking threshold and its effect on fatigue performance.
- Improve rope designs and fiber finishes to optimize fatigue performance.
- Analyze existing field applications with load data acquisition.

3.2. Breakout Session

The following questions were provided to the participants to answer either verbally or by typing in a response. The first question in this list was presented standalone and was used as a key question to guide participant discussion, while the following questions were presented all at once for participants to answer at their own pace:

- Do we have a good framework for effectively monitoring the degradation of synthetic mooring lines during deployment?

- What monitoring capabilities exist in a testing environment and what are the challenges facing widespread integration (either in situ or ex situ)?
- What monitoring capabilities exist in an operational environment and what are the challenges facing widespread integration (either in situ or ex situ)?
- What is your willingness to trust an automated monitoring system?
- How do you quantify mooring line failure and when replacement is required?
- Do you think we have a well-established system for evaluating damage tolerance for any given design?
- How do you monitor failure, and what types of failure mechanisms do you consider when designing mooring line capability for WECs or TECs?

In response to the first question, participants generally felt that the current framework for degradation monitoring of synthetic mooring lines was either nonexistent or in the early stages of development. Key concerns focused on a lack of established methods, frameworks, or standards for characterizing performance. Similar to the items discussed by Mark in his presentation, experimental scalability accuracy, in situ sensor/measurement technology development, and low-cost characterization were the primary focus areas needed to accelerate our understanding of material performance.

Answers to the remaining questions had similar feedback from participants. Participants agreed that prevailing practices such as visual inspections cannot sufficiently detect internal abrasion or fiber-level fatigue. Advancements in fiber optics and acoustic systems were discussed as promising alternatives for obtaining robust real-time assessment of performance, but these options primarily remain within early R&D stages of development. Additionally, their effect on rope integrity is likely minimal, but their durability may be limited, especially in high-strain materials. Lastly, marine growth was discussed as another barrier that further complicates inspection and removal processes for performance detection. Practical options discussed by participants for reducing biofouling growth included deploying submersible winches or swivel hoist rings to remove growth.

The topic of developing a digital twin garnished much interest for predicting remaining life and optimizing maintenance schedules. These models once developed would ultimately rely on real-time load and motion data to make real-time fatigue tracking and predictive maintenance. However, there currently exists no known method for obtaining the necessary data needed for validation of these types of models.

4. TESTING FACILITIES, CHARACTERIZATION CAPABILITIES, AND STANDARDS

4.1. Presentation

A presentation on testing facilities, characterization capabilities and standards was given by Budi Gunawan from Sandia National Laboratories. Budi has a background in experimental and numerical fluid dynamics with an ongoing focus on laboratory/field testing, modeling, and prototype development within marine energy applications. See page 63 for slides that were presented. His talk summarized examples of various companies leveraging mooring lines and belts within their current WEC applications. He also discussed current projects that focus on the development of testing facilities that will enable large-scale testing for validating mooring line, belt, and umbilical cable performance. Future work discussed included updating standards for testing, executing testing campaigns to develop comprehensive datasets needed for modeling boundary conditions and inputs, and sharing these results with the community.

For future direction, Budi identified the following as key focus areas:

- Find the most appropriate test methods and analysis procedures for given test article properties, loading mechanisms, and deployment conditions.
- Conduct mooring testing campaigns that use field/numerical model boundary conditions as inputs.
- Improve rope designs and fiber finishes to optimize fatigue performance.
- Develop a database for mooring testing results.

4.2. Breakout Session

The following questions were provided to the participants to answer either verbally or by typing in a response. The first question in this list was presented standalone and was used as a key question to guide participant discussion, while the following questions were presented all at once for participants to answer at their own pace:

- Do we have the right capabilities to evaluate mooring line performance and material response?
- Do we have sufficient standards to follow for mooring line design, materials selection, manufacturing, testing, service life, etc.?

- Prior to testing, what materials do you supply and what resources do you need for a given testing facility?
- What do you hope to characterize in terms of measurements and uncertainties?
- What are the current equipment limitations (lab and field settings) you have experienced and what do you wish you could measure?
- Do we have the capability to test various mooring line types (various materials, braiding, etc.)?
- What instrumentation improvements are needed?

In response to the first question, participants generally felt that current testing facilities are limited. Of the facilities that currently exist, there was large uncertainty on whether the testing capabilities were representative to the length scales needed for real-world applications. In other words, it is unknown if laboratory-scale experiments can accurately capture real-world conditions for full-scale rope constructions. Key limitations noted included large-scale, long-term fatigue testing under wet/saturated conditions with exposure to biofouling within a controlled environment. Numerous key challenges were identified that limit existing testing capabilities: 1) the inability to scale results from a laboratory setting to full-scale tests; 2) uncertainty and inability to properly instrument mooring lines at scale to measure local loads or displacements; 3) cost and accessibility, with several developers mentioning the inability to afford large-scale testing; 4) lack of standardized testing; 5) the effects of biofouling remain poorly understood and are rarely tested under controlled conditions.

Availability at current testing facilities is limited. Proposed facilities will soon come online, such as the Sandia Line Inspection and Guided Hardware Testing (LIGHT) facility. However, additional facilities are required to meet the community's demand, given the time-intensive nature of cyclic-fatigue testing. Additional testing capabilities will also enable the opportunity to inform community-wide standards and workflows needed to ensure cumulative learning among the community, thus generating much needed institutional knowledge in mooring design to accelerate deployment.

Similar results were found from the answers to the remaining questions. Participants emphasized the need for full-scale, long-duration fatigue testing to validate subscale results. Instrumentation gaps were highlighted with a call to further develop robust in situ load cells with adequate power and data transfer capabilities needed for real-time measurements. There was also a call for clear guidance on integration locations for sensors such as buoy surfaces, mid-line location, and at or near the anchor points.

5. MODELING CAPABILITIES AND NEEDS

5.1. Presentation

In the modeling topic, a presentation was given by Stein Housner from the National Laboratory of the Rockies. Stein is a floating offshore energy system engineer with a primary research focus on the modeling and design of mooring systems and floating platforms for offshore systems. See page 71 for slides that were presented. His presentation focused on existing modeling capabilities within a versatile, lumped-mass dynamic mooring model named MoorDyn, as well as simplified capabilities in MoorPy. Recent developments were discussed on the implementation of viscoelastic models in these codes to better reflect the behavior observed experimentally. An outstanding challenge is the significant lack of public testing data needed for model validation. Future direction could involve collaborating with experimentalists to plan large-scale testing campaigns for various rope types and sizes, processing test results to fit within standard modeling parameters, and publishing data.

For future direction, Stein identified the following as key focus areas:

- Expand MoorDyn to implement state-of-the-art viscoelastic models, matching the fidelity of proprietary approaches.
- Convene research, rope manufacturers, and system designers to agree on standard modeling approaches and parameter sets to use across applications.
- Set up joint avenues for testing plans, facilities, and industry partners.
- Perform a large testing campaign across many rope types and sizes.
- Process test results that are suitable for fitting to standard model input parameter sets.
- Publish data.

5.2. Breakout Session

The following questions were provided to the participants to answer either verbally or by typing in a response. The first question in this list was presented standalone and was used as a key question to guide participant discussion, while the following questions were presented all at once for participants to answer at their own pace:

- Do current modeling capabilities accurately predict performance of synthetic mooring lines within representative environments?
- What approaches are used to determine mooring line loading conditions?

- When designing synthetic mooring lines, what level of fidelity and length scale are you most concerned about?
- What software or tools do you use for your modeling needs and what are their limitations?
- What data are needed to run these models?

For the first question, participants agreed that either current modeling capabilities do not accurately predict synthetic mooring line performance or existing capabilities possess significant knowledge gaps when predicting performance. These gaps include inability of modeling with high fidelity to incorporate time-dependent properties across length scales, experimental data and validation gaps, robust material properties sets for inputs, inability to predict aging/degradation, failure mechanisms are currently underrepresented, and existing software necessitates a large learning curve for new users.

With respect to the remaining questions, similar results were found. It was discussed that approaches to mooring line loading are commonly determined using design-level environmental conditions such as 100-year waves and currents. Both frequency-domain and time-domain simulations that couple hydrodynamics and mooring dynamics primarily leverage lumped-mass solvers or linear potential-flow models to make predictions. Example codes that make predictions by leveraging lumped-mass solvers or linear potential-flow models include MoorDyn [4] or OrcaFlex (Orcina Ltd, Daltongate, Ulverston, Cumbria, UK).

Ultimately, the appropriate modeling approach depends on the needed fidelity. Participants noted that material properties are frequently oversimplified. Failure and degradation physics are commonly simplified or omitted, but their impact on performance should be included in future modeling iterations. A phenomenon mentioned that has not been thoroughly studied is the impact of vortex shedding on mooring lines due to various current speeds. To date, studies choose to neglect the impact of computational fluid dynamics due to simulation costs.

As mentioned previously, additional modeling needs to improve capability include developing digital-twin across length scales, standardizing validation workflows against open-water data by constant collaboration among modelers and experimentalists, and generating material databases that span a wide variety of rope materials, loading conditions, environmental conditions, and large timescales.

6. FUTURE DIRECTIONS

The workshop was designed to identify materials of interest, assess their current limitations, define the testing data needed to support their evaluation, and determine where modeling capabilities for synthetic mooring ropes require further development. These objectives were successfully met, and the resulting findings provide a strong foundation for guiding future research and development efforts aimed at reducing technological barriers and improving material reliability and performance. The preceding discussion topics offered a detailed assessment of the key research gaps and technical challenges facing the marine energy community in the deployment of synthetic mooring lines. Table 6-1 summarizes the key research and development needs identified by workshop participants. Collectively, these findings will help inform a more comprehensive strategy for future research, testing, and technology development efforts.

Table 6-1. Research and development needs for advanced synthetic mooring lines in marine energy.

Category	R&D needs
Materials	• Evaluate polyethylene, polyester, nylon, aramid, and liquid crystal polymer materials • Improve fatigue, creep, abrasion, UV, and biofouling resistance • Generate public data from fiber to full-line scales • Develop hybrid rope designs and braiding architectures • Improve terminations, splices, and hardware interfaces • Assess cost, manufacturability, and domestic supply • Address recyclability and end-of-life impacts • Differentiate needs by device type and environment
Failure, degradation, and monitoring	• Establish degradation and remaining-life frameworks • Identify key failure and degradation mechanisms • Study low-amplitude fatigue under high mean loads • Quantify strength retention over service life • Develop monitoring for internal, nonvisible damage • Advance fiber-optic and acoustic sensing methods • Evaluate sensor impacts on rope integrity • Address monitoring challenges from biofouling • Define damage limits and replacement criteria • Enable predictive maintenance and digital twins

Category	R&D needs
Testing, characterization, and standards	• Expand full-scale, long-duration test capability • Replicate wet, cyclic, abrasive, and biofouling conditions • Improve scaling from lab to field performance • Measure distributed load, strain, and damage • Improve sensor power, communication, and durability • Develop standardized testing and reporting protocols • Define standard sensor locations and workflows • Create shared benchmark datasets • Improve test access and affordability • Quantify biofouling effects under controlled conditions
Modeling	• Include viscoelasticity, creep, fatigue, and degradation • Develop multiscale models from fiber to system level • Incorporate failure physics into design models • Build validated material-property databases • Validate models with lab and field data • Standardize calibration and validation workflows • Develop digital twins for life prediction • Improve coupled wave, current, and hydrodynamic modeling • Improve usability and guidance for modeling tools • Translate experiments into model input parameters

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Appendices

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APPENDIX A. Workshop Agenda and Timeline

Table A-1. Workshop Agenda.

Thursday, December 11, 2025, 9:30 – 13:20 MST	
Time	**Agenda Item**
09:30–09:35	Welcome
09:35–10:00	Workshop Overview, Past Workshops Review, and Workshop Takeaways
10:00–10:05	Transition
10:05–10:20	Materials: past, present, and future Presenter: Peter Davies, Institut Français de Recherche pour l'Exploitation de la Mer
10:20–10:35	Breakout
10:35–10:45	Free-response & Polling Questions
10:45–10:50	Summary
10:50–11:05	Expected Failure Mechanisms, Environmental Degradation, and Health Monitoring Presenter: Mark Huntley, Whitehill Manufacturing Corporation
11:05–11:20	Breakout
11:20–11:30	Free-response & Polling Questions
11:30–11:35	Summary
11:35–11:45	Break
11:45–12:00	Testing Facilities, Characterization Capabilities, and Standards Presenter: Budi Gunawan, Sandia National Laboratories
12:00–12:15	Breakout
12:15–12:25	Free-response & Polling Questions
12:25–12:30	Summary
12:30–12:45	Modeling Capabilities and Needs Presenter: Stein Housner, National Laboratory of the Rockies
12:45–13:00	Breakout
13:00–13:10	Free-response & Polling Questions
13:10–13:15	Summary
13:15–13:20	Close Out and Adjourn

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APPENDIX B. Workshop Feedback

Participants provided candid feedback on the workshop, with several expressing dissatisfactions over logistical issues and reliance on polling and participant-generated input rather than presenting technical content. Common concerns included registration and platform access difficulties, limited time for in-depth presentations, and the use of polling and free-response software XLeap combined with Microsoft Teams for servicing audio, visual, and virtual breakout rooms. Several attendees felt this added unnecessary complexity and detracted from discussion. Many participants suggested that future workshops use simpler platforms and provide clearer communication and smoother logistics.

At the same time, attendees recognized the value of the expertise represented in the workshop and highlighted several technical presentations as informative and worthwhile. Looking ahead, participants recommended that future workshops place greater emphasis on knowledge sharing, best practices, and actionable technical outputs as these research developments become available. Specific suggestions included focusing more directly on developer needs, providing longer and more detailed presentations, standardizing testing data expectations, and designing workshop formats that deliver clearer practical value to the marine energy community.

The organizing committee thanks the participants for their feedback. We sincerely value this input and look forward to addressing the feedback provided and improving clarity when planning future workshops.

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APPENDIX C. Workshop Presenter Slides

Below are the slides the presenters prepared for the four focus areas.

Sandia National Laboratories

Exceptional service in the national interest

Ifremer

SYNTHETIC MOORING LINES WORKSHOP

Topic #1: Past, present, and future materials

Peter Davies

Materials Laboratory

IFREMER, French Ocean Research Institute

December 11th 2025

U.S. DEPARTMENT of ENERGY NNSA

BACKGROUND

Ifremer

- **Brief introduction**: Our laboratory at IFREMER has been working on Marine Materials for over 40 years. The marine rope R&D activity started in the 1990's for <u>oceanography and deep sea handling</u>, (we are also a rope user), then with the offshore <u>Oil & Gas industry</u> for 15 years, and since 2015 for **offshore renewable energy**.

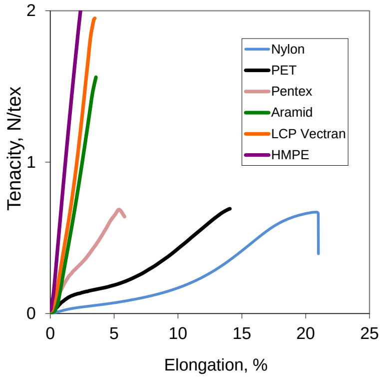
- **State of the Art:**

The past	Today	The future ?

>300 years natural fibres

e.g. hemp

Synthetic fibres (since 1950's)



Special Constructions

- **New fibers**
- **Hybrid ropes**
- **Synthetic chains**
- **Elastomer dampers**
- **???**

OUTSTANDING CHALLENGES OF TOPIC #2

1. **Material selection needs data** (characterization):

- Many options: Chemistry/Formulation, Stretching, Construction, Heat setting. Quality control ?
- Dynamic properties, Realistic (stochastic) loads, Friction measurements.
- Scale effects ? Terminations ?

2. **Long term durability: HMPE & PET OK, PA6 not proven**:

- Need high cycle fatigue data but expensive. Role of coatings ?
- Coupling: Moisture affects both Short & Long term response

3. **Must include environmental impact in design**

- Data on environmental impacts ?
- End-of-life: Recycling options, Novel materials ?

Nylon SPM (JIP OHDYLE)

Nylon outer braid, 2 years at sea

Ifremer

FUTURE DIRECTIONS

1. **Generate more reliable fatigue data for polyamide and make it available.**

2. **Benefit from experience of mooring lines at sea; instrumentation, residual properties**

3. **Develop rope recycling, alternative material options, LCA**

Moored with nylon since 2018

GEPS, WAVEGEM

Projects underway are examining various aspects of these directions,
but a coordinated effort is needed.

Sandia National Laboratories

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SYNTHETIC MOORING LINES WORKSHOP

Topic #2: Expected failure mechanisms, environmental degradation, and health monitoring

Mark Huntley, Ph.D.

Whitehill Manufacturing Corporation

December 11, 2025

U.S. DEPARTMENT of ENERGY NNSA

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BACKGROUND

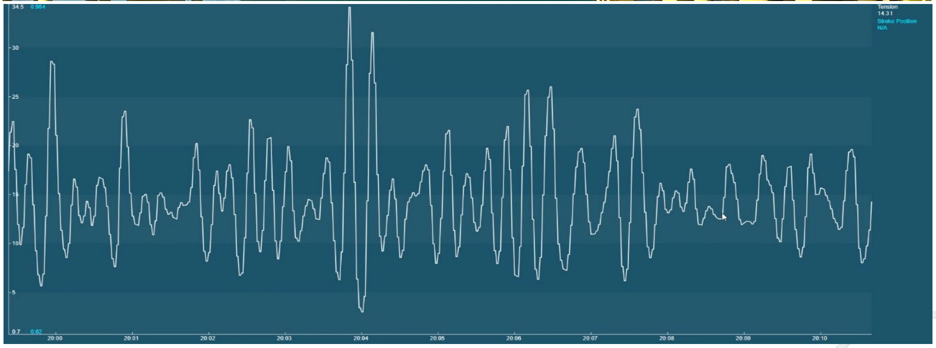
- Whitehill founded in 1978 to specialize in high performance synthetic rope
- Focus on application-specific products
- Manufacture over 450 rope constructions
- Whitehill has provided polyester mooring lines for six permanent production platforms in the Gulf of Mexico

MOORING LINES FOR MARINE ENERGY

- Marine energy applications (WEC and FOW) typically require shallow water moorings, opposed to deepwater O&G mooring
- Dynamics in shallow water can be high due to the shorter mooring lengths relative to wave heights, which require a low-modulus mooring line (typically nylon)
- The predominant failure mechanism for nylon is tension-tension fatigue
- Knowledge of rope fatigue characteristics is not well established, but critical for successful long-term deployments

CASE STUDY: BP *TORTUE* FLNG FACILITY MOORING SYSTEM

- Offshore Senegal / Mauritania
- Shallow water mooring
- Nylon mooring lines
- 30-year design life
- Tension records for each line
- Periodic line removal scheduled
- Service life to be determined from field test data



WHAT IS THE SERVICE LIFE FOR NYLON MOORING LINES?

CHALLENGES:

#1: S-N fatigue curve for nylon is not well established

#2: Laboratory fatigue data for nylon ropes is limited due to significant cost and time associated with testing of full-scale ropes . Testing of scaled ropes is faster and cheaper, but accuracy of scaling creates an additional unknown.

#3: Service life predictions have a high degree of inaccuracy, since they are based on extrapolations of test data.

TEST DATA

Low # of Cycles & High Amplitude

→

MOORING APPLICATION

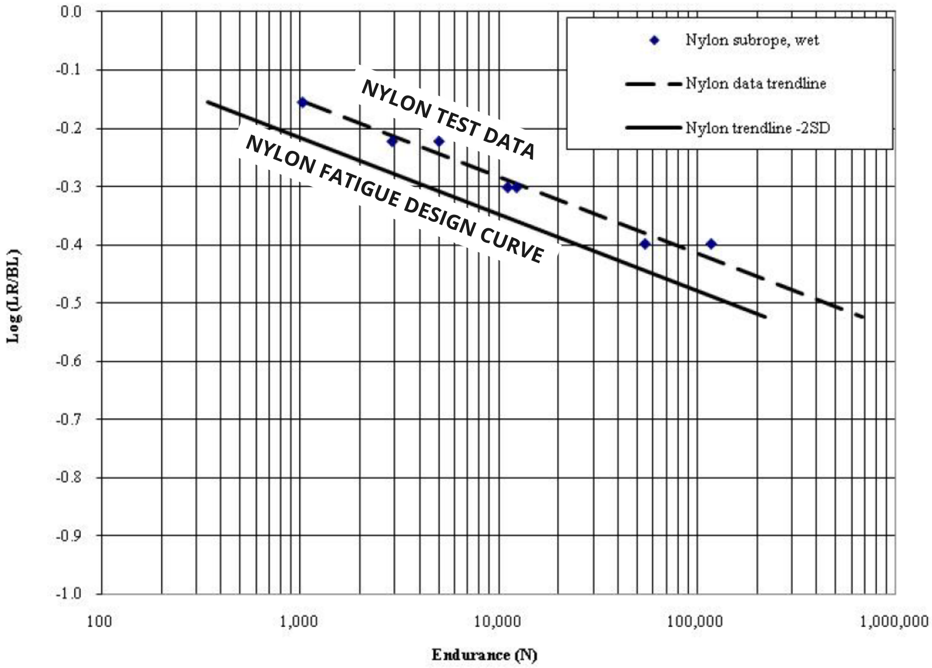
High # of Cycles & Low Amplitude

RECENT LITERATURE ON NYLON FATIGUE PERFORMANCE

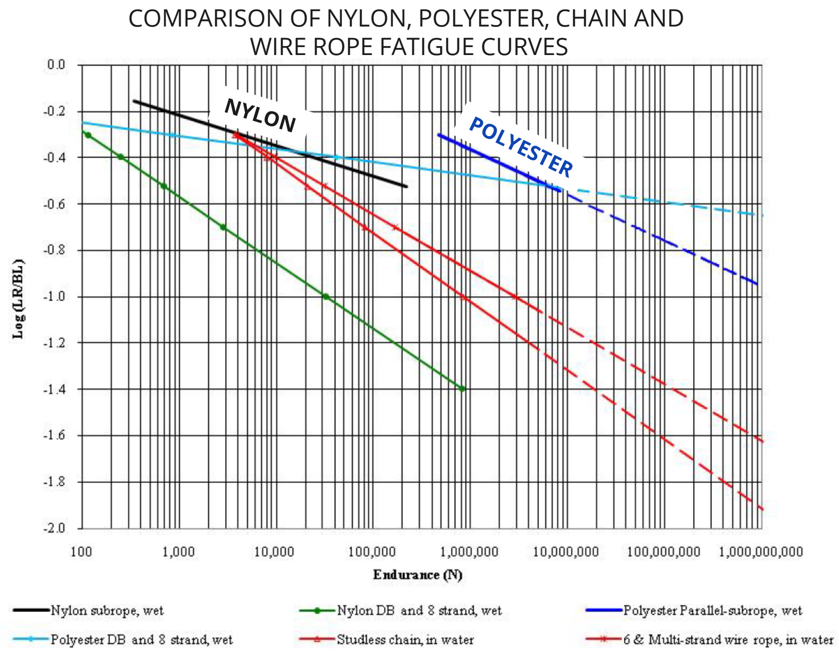
- RIDGE et al., 2010 MTS/Oceans Conference
- Huntley, 2016 MTS Oceans Conference
- Ridge and Banfield, 2017 MTS/Oceans Conference
- Chevilotte et al, 2019 Ocean Engineering
- Huntley and Huntley, 2023 OIPEEC Conference

NYLON S-N CURVE BASED ON LIMITED TEST DATA (RIDGE ET AL., 2010)

LOG-LOG ANALYSIS OF TEST DATA



FATIGUE DESIGN CURVES (RIDGE ET AL., 2010)



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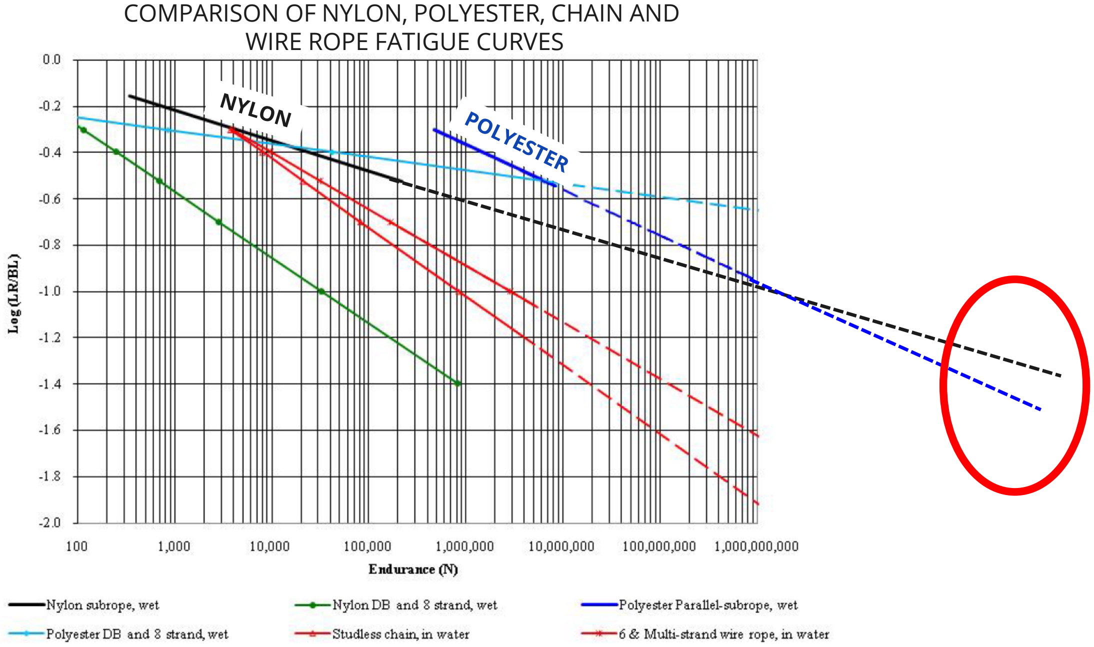
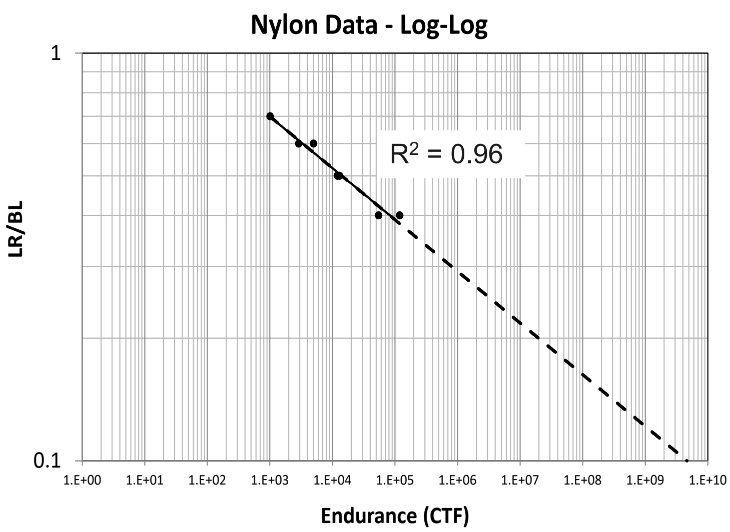
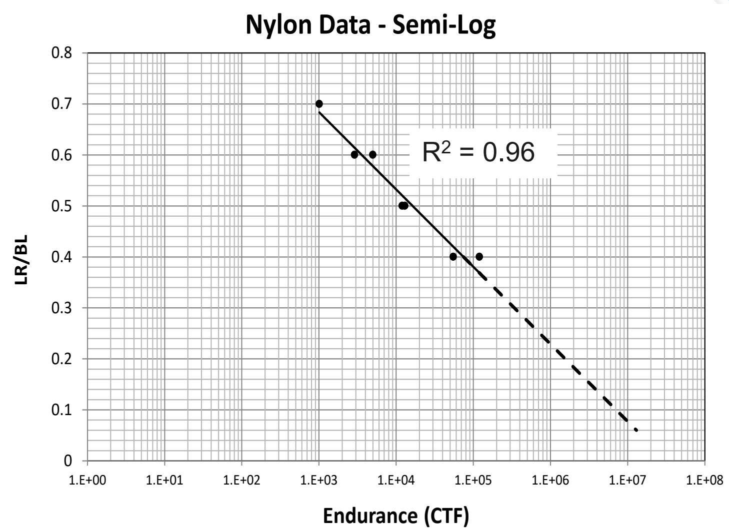


BE CAREFUL!

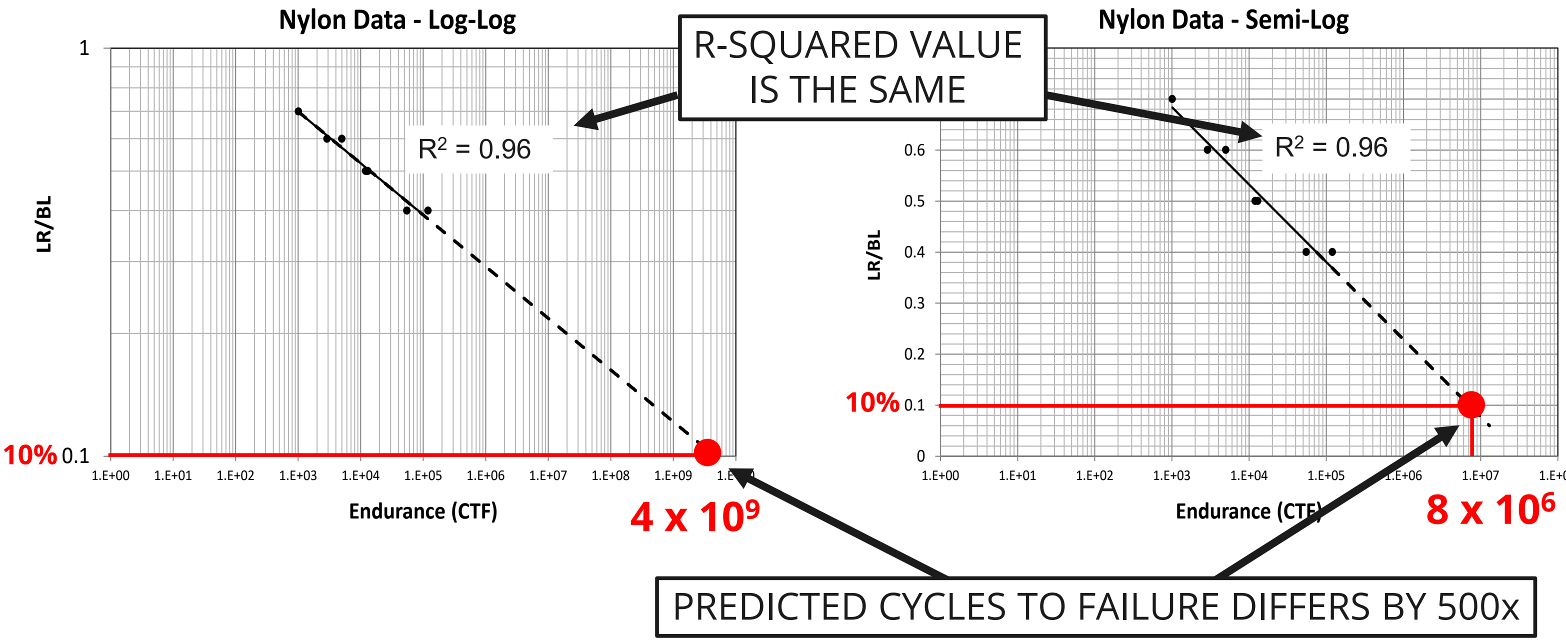
LOG-LOG ANALYSIS PREDICTS THAT NYLON WILL OUTPERFORM POLYESTER

DATA EXTRAPOLATION: LOG-LOG VS SEMI-LOG





DATA EXTRAPOLATION: LOG-LOG VS SEMI-LOG

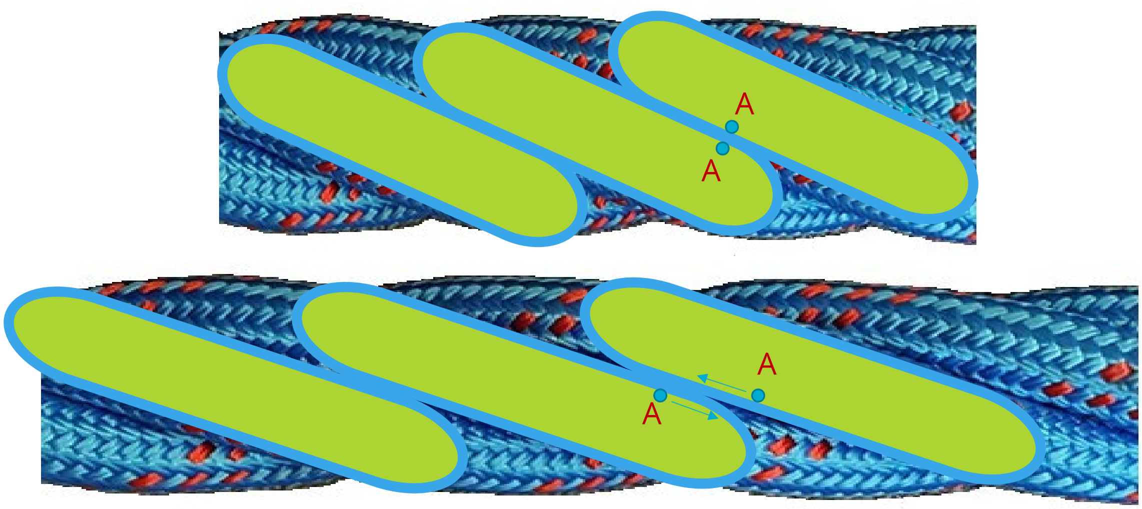


WHY IS THERE SO MUCH UNCERTAINTY FOR NYLON FATIGUE?

- Nylon fatigue failure is typically governed by internal abrasion in the rope structure
- For high amplitude cycling, internal abrasion is always present to some degree, especially in the rope spliced terminations
- For low amplitudes and high mean loads, the rope structure is effectively frozen and no abrasion takes place. This phenomena is referred to as Mean Load Locking

CASE 1: LARGE AMPLITUDE CYCLES

- Movement occurs between adjacent strands
- Strain amplitude exceeds frictional force between strands
- Strand-on-strand abrasion causes strength loss



TROUGH LOAD

PEAK LOAD

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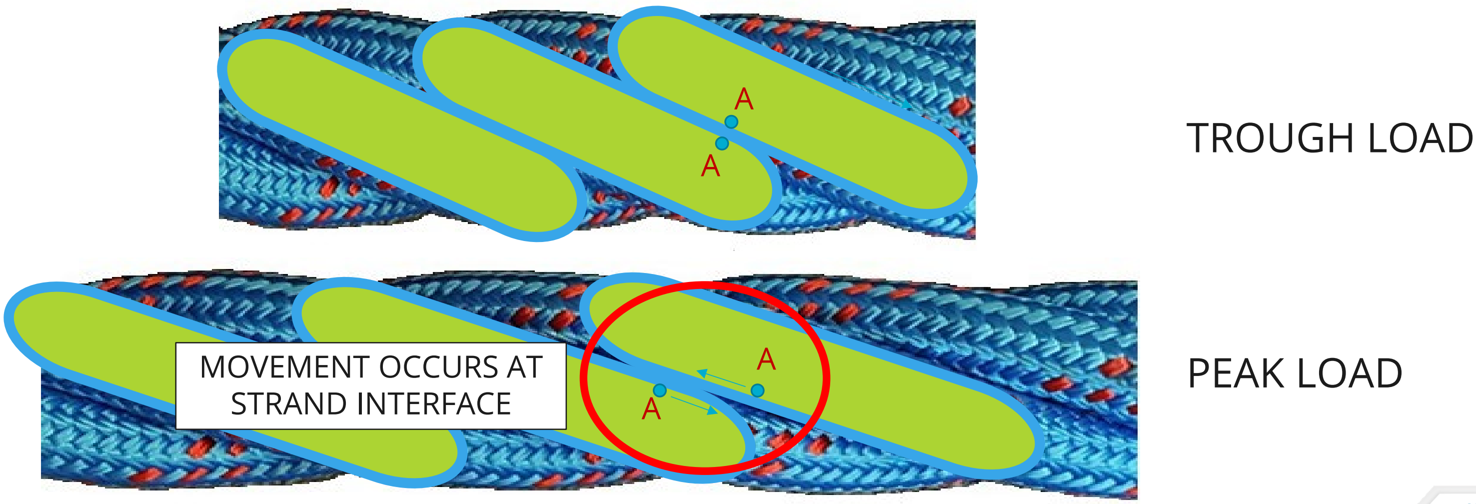
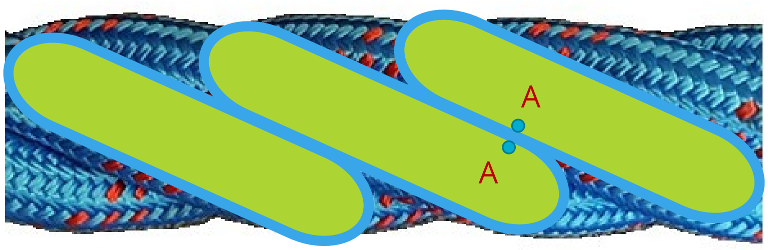
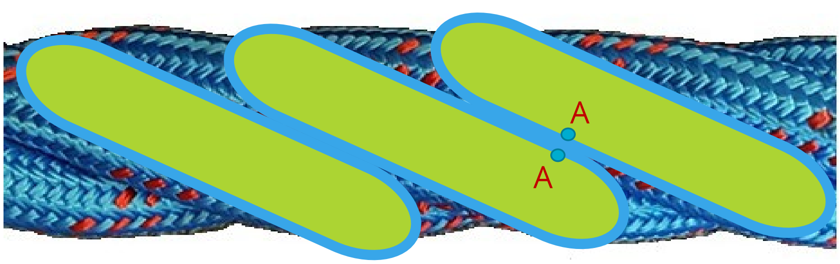


CASE 2: SMALL STRAIN AMPLITUDE & HIGH MEAN LOAD

- “Mean Load Locking”: No relative movement, <u>no abrasion</u>
- High normal force resists movement at strand interface
- High stiffness limits strain amplitude



TROUGH LOAD



PEAK LOAD

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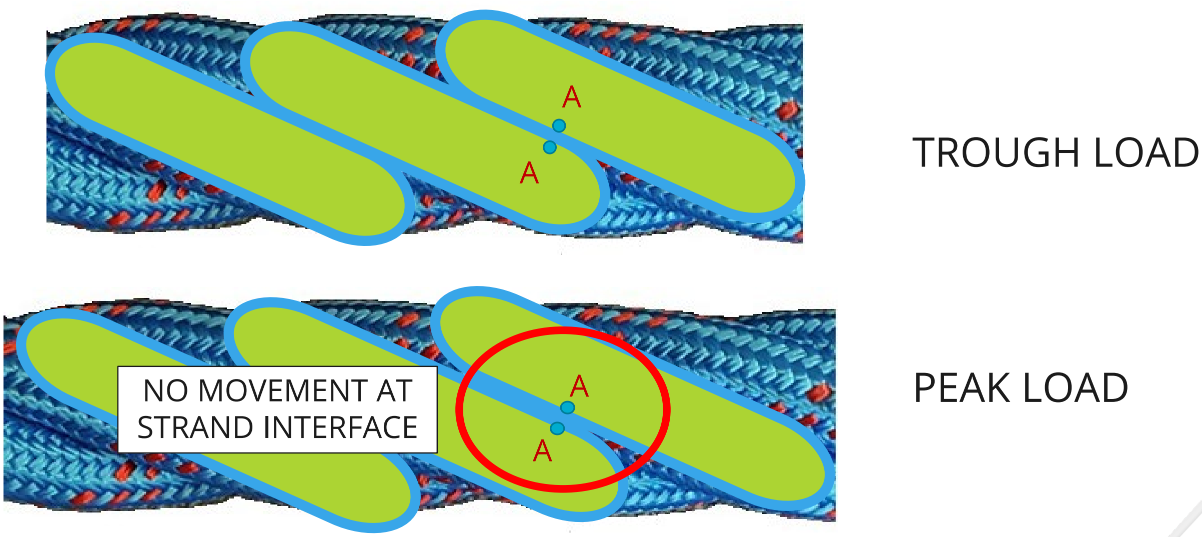
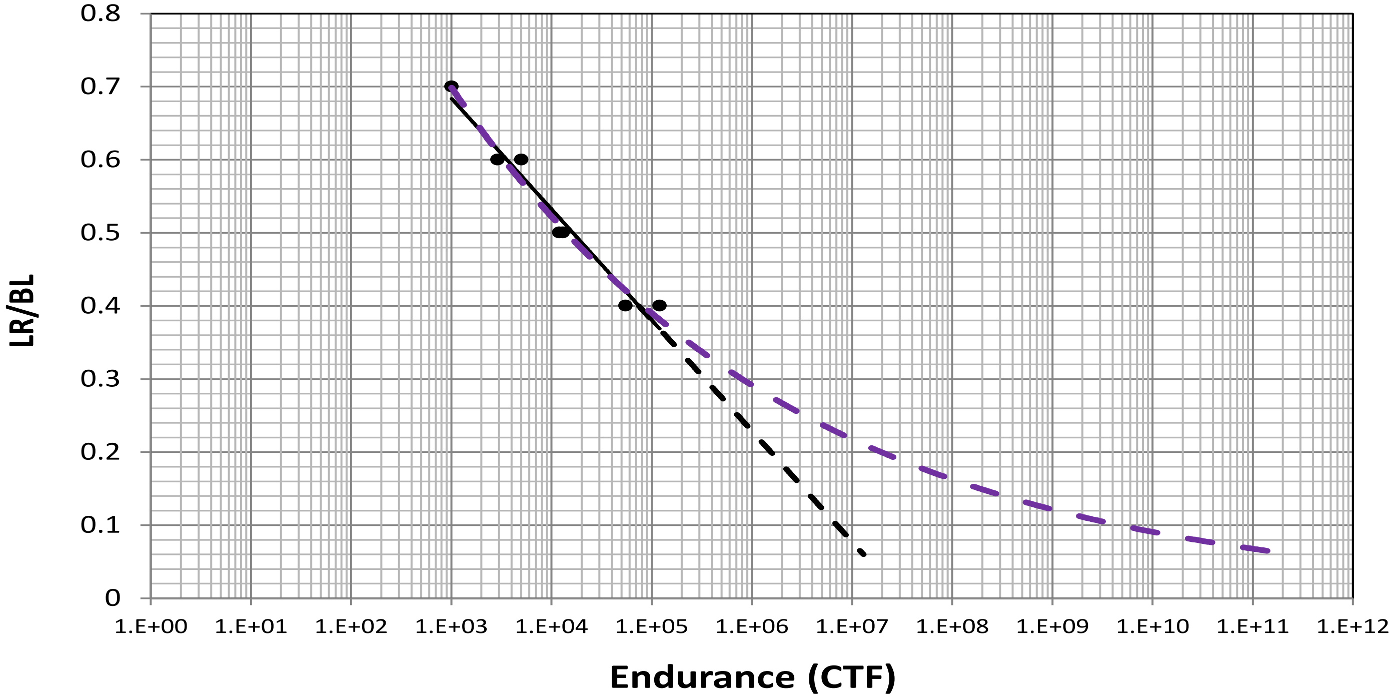


WHAT IS THE EFFECT OF MEAN LOAD LOCKING ON FATIGUE?



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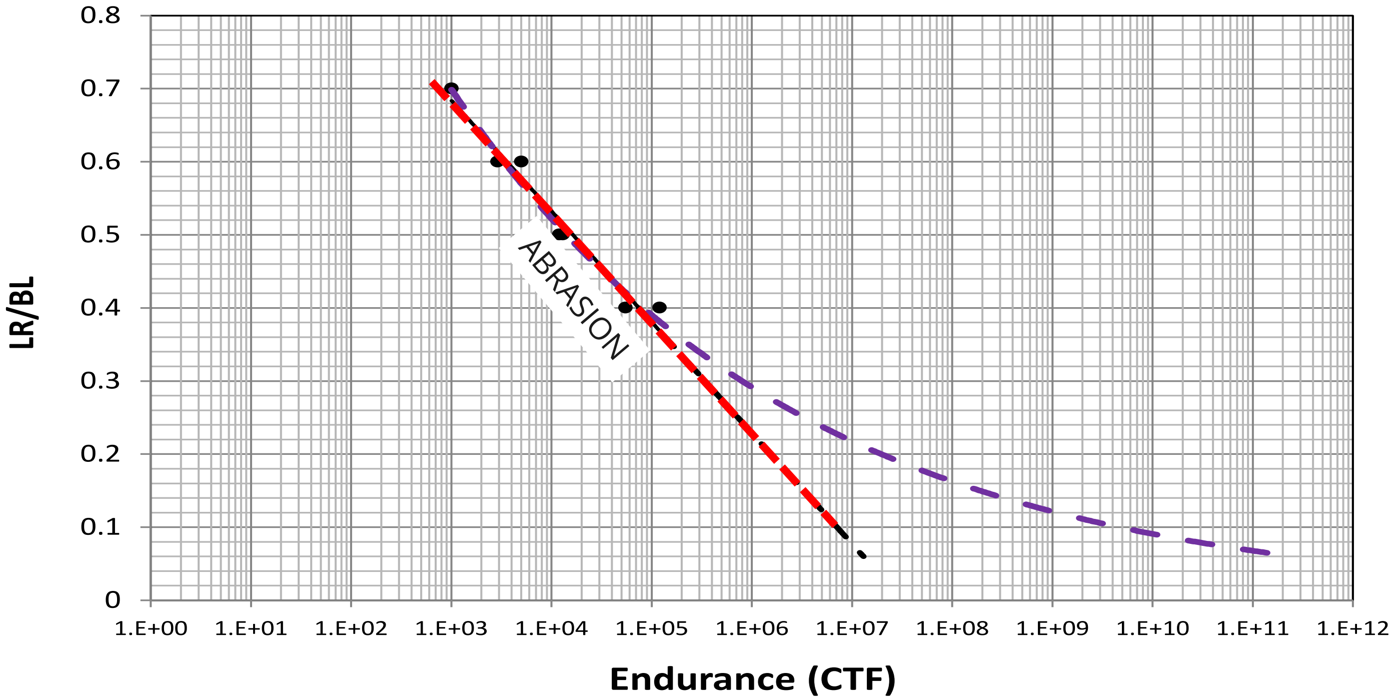

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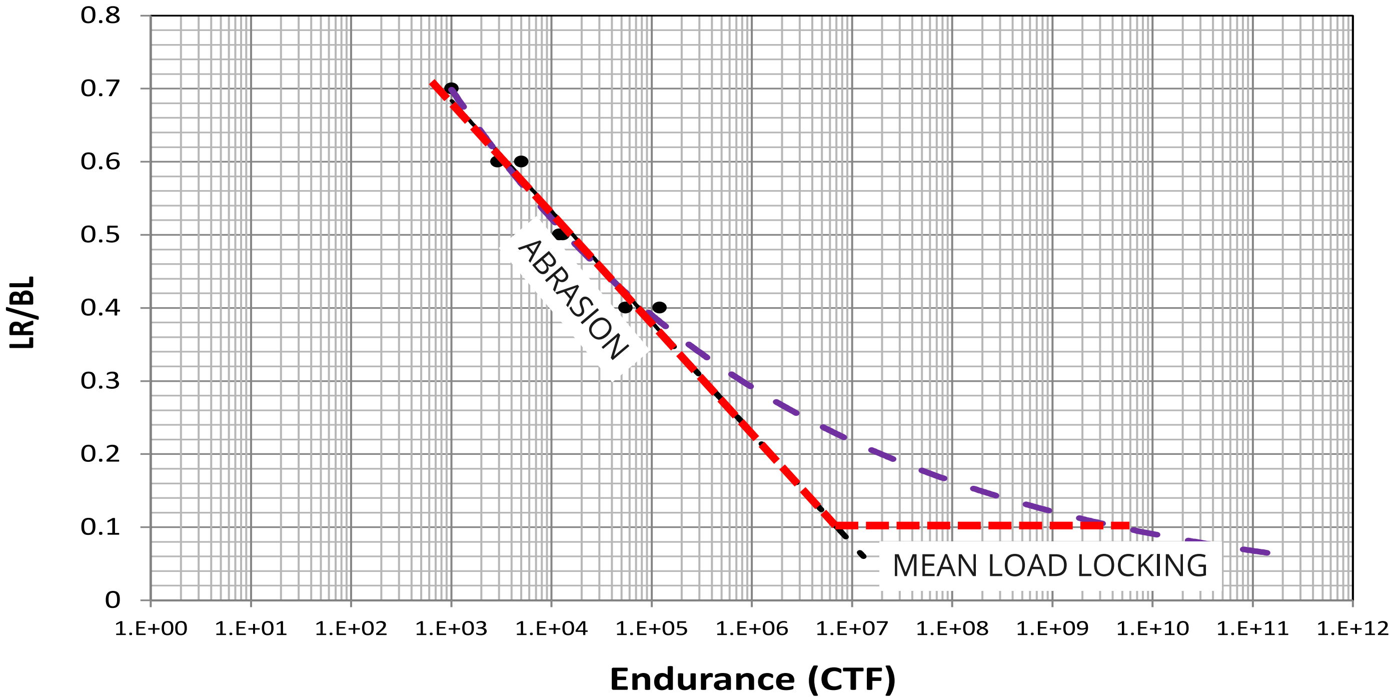
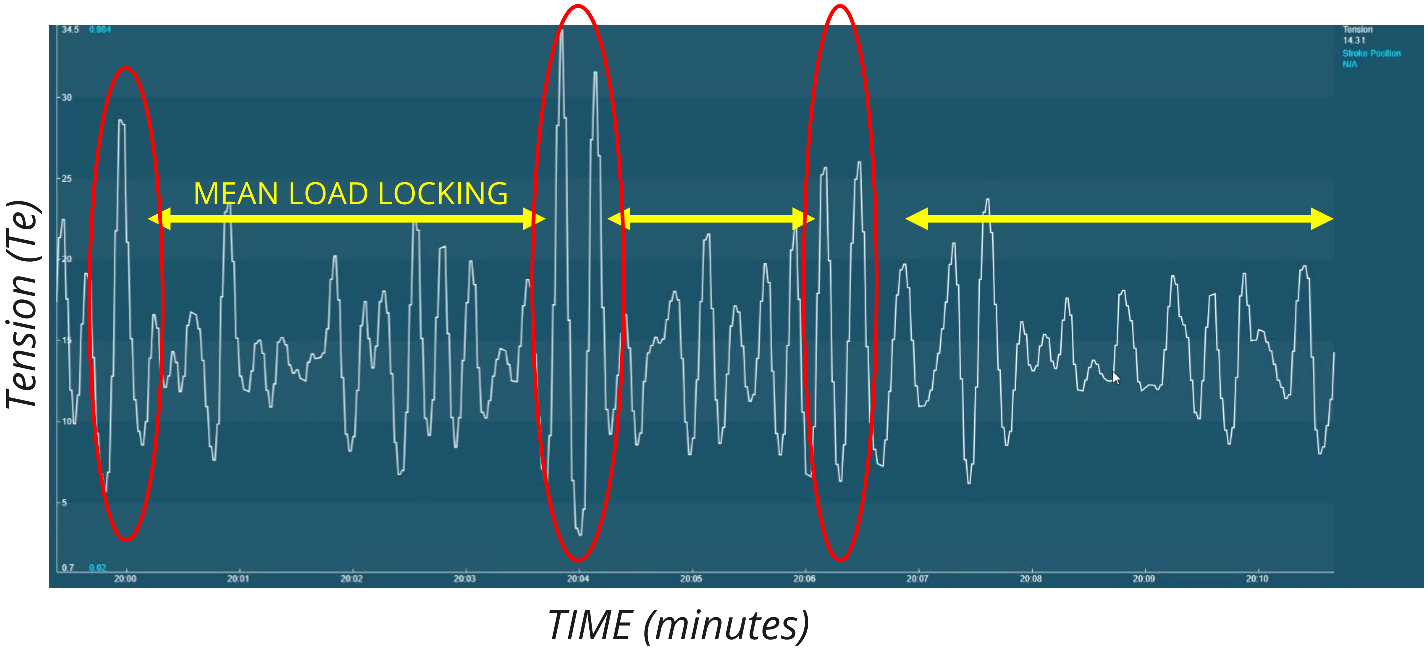


IMPLICATIONS FOR BP *TORTUE* TENSION DATA

- Mean Load Locking occurs for 25 of 30 cycles – No abrasion damage
- 5 cycles exceed the locking threshold and would result in abrasion damage



FUTURE DIRECTION

- Improve understanding of nylon fatigue performance at low amplitudes
  - May require dedicated test facility capable of high frequency cycling
  - Need to address rope scaling issue
  - Need to be careful of rope internal heating

- Improve understanding of mean load locking threshold and its effect on fatigue performance

- Improve rope designs and fiber finishes to optimize fatigue performance

- Analyze existing field applications with load data acquisition
  - Validate nylon fatigue properties
  - Determine rope strength retention characteristics as a function of applied cycles

SAND2025-15071PE

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SYNTHETIC MOORING LINES WORKSHOP

Topic #3: Testing facilities, characterization capabilities, and standards

Budi Gunawan, Ph.D.

Sandia National Laboratories

December 11, 2025

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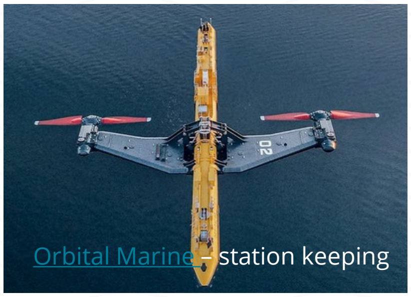
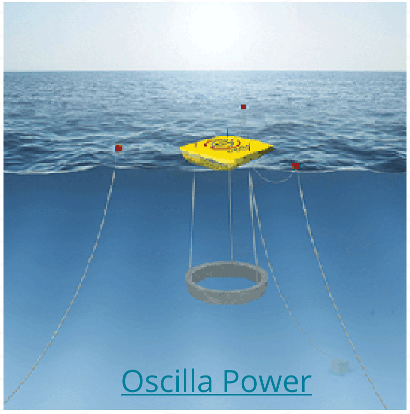
BACKGROUND

- The mooring lines of wave energy converters (WECs) experience between 3 to 6 million load cycles during a one-year deployment
- Mooring lines and belts functions for WECs and CECs:
  - Station keeping
  - Reaction force pathway for PTO – unique loading profile
- Key questions: How often should they be replaced? How and when will they fail?


Orbital Marine – station keeping

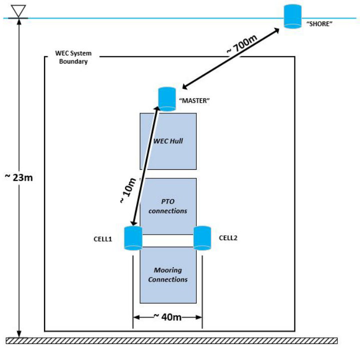

AquaHarmonics

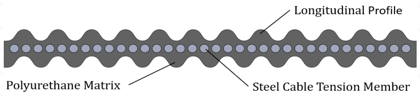
CalWave

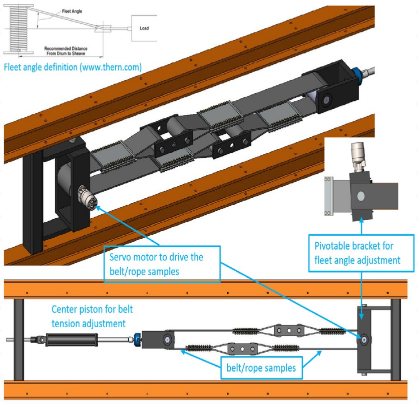

Oscilla Power

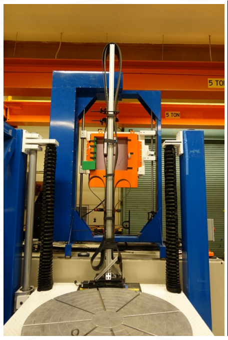
PRIOR MOORING BELT TESTING: CALWAVE PILOT STUDY

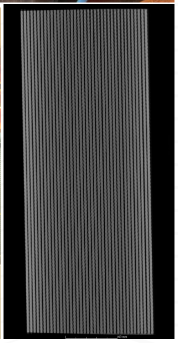
CalWave deployment (2021)





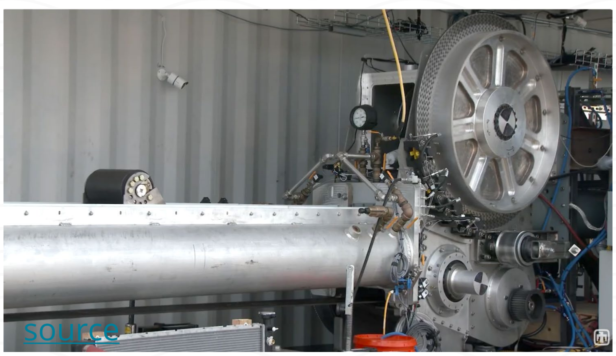


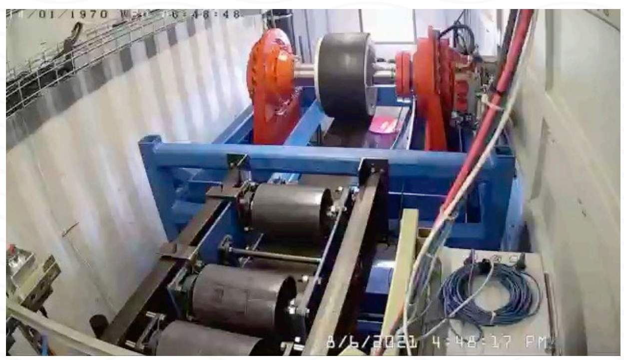




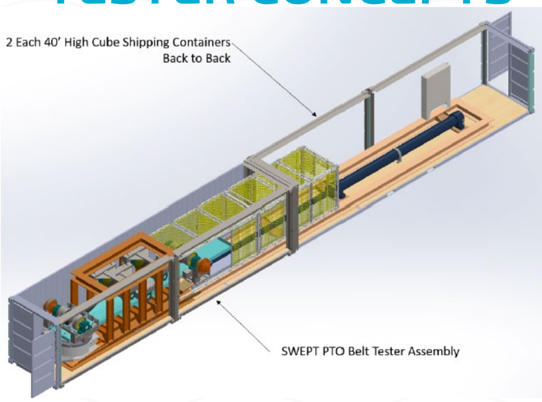
The belt PTO performance was verified using cyclic bend over sheave (CBOS) testing and NDI

SANDIA WAVE POWER TAKE-OFF LAB





TESTER CONCEPTS



Belt tester

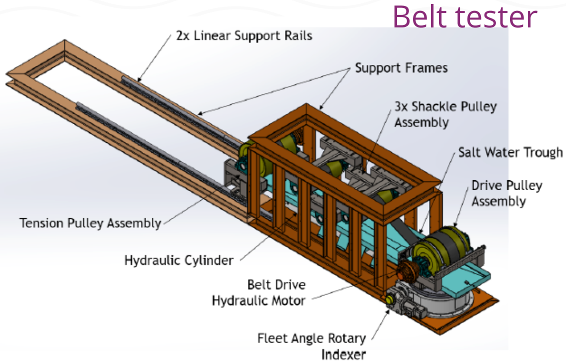
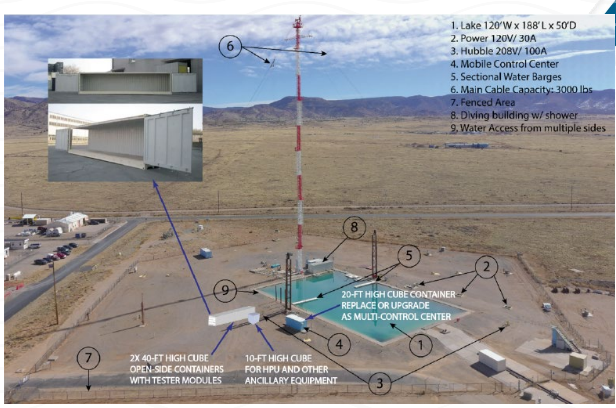
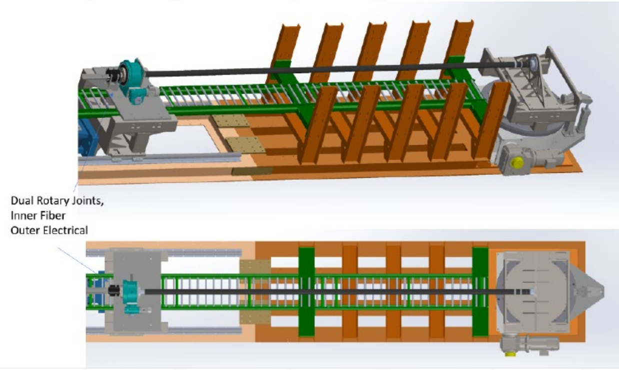


Figure 13 – Proposed Latest Concept of the Belt Tester Assembly





MARINE ENERGY LINE TESTING SURVEY (2021)

Materials of interest
Nylon (Polyamide or PA)
Liquid crystal polymers (LCPs)
Polyester (PET)
Hybrid materials
Polypropylene (PP)
Polyolefins (i.e. HMPE or HPPE)
High-modulus, high-tenacity fibres (i.e. Aramid)
steels/stainless steel belt elements
Steel, Stainless Steel, polyurethane, carbon fiber
steel cord, PBO (p-phenylene-2,6-benzobisoxazole), carbon fiber
Any rope construction which helps to absorb peak loads; high MBL and low stiffness

Type of testing
Breaking strenght
Load - strain response
Torsion
Tensile fatigue
Cyclic bend over sheave
Non-destructive inspection, e.g. X-ray
Tensile/load frame (e.g. using Instron machine)
Accelerated aging
Corrosion analysis, influence of salt water to the bonding between rubber and fabric

Component of interest
PTO belt
PTO rope
Mooring line
Umbillical
Electrical, Optical, Mechanical cable

Damage mechanism of interest
Creep
Shock loading
Fatigue/friction
Exceedence of minimum breaking strenght
Compression fatigue
UV exposure
Wetting/drying
Biofouling
Cyclic bend over sheave (CBOS)
Abrasion

CHALLENGES

- The ME industry is lacking of:
  - Standards that details the mooring testing requirements/procedures
  - Mooring line retirement criteria
  - Open-source data on mooring measurements/testing
- There are many different WEC archetypes:
  - Critical failure mechanisms are unique to the mooring materials being used and loading profile specific to the WEC
  - How to represent the unique operation mechanism in a lab-based testing?
- Lab testing challenges:
  - Fatigue testing takes some time
  - Uncertainty could be high for low number of test sample & result extrapolation
  - Representing environmental/other factors: wetting, abrasion, tear, UV, etc.

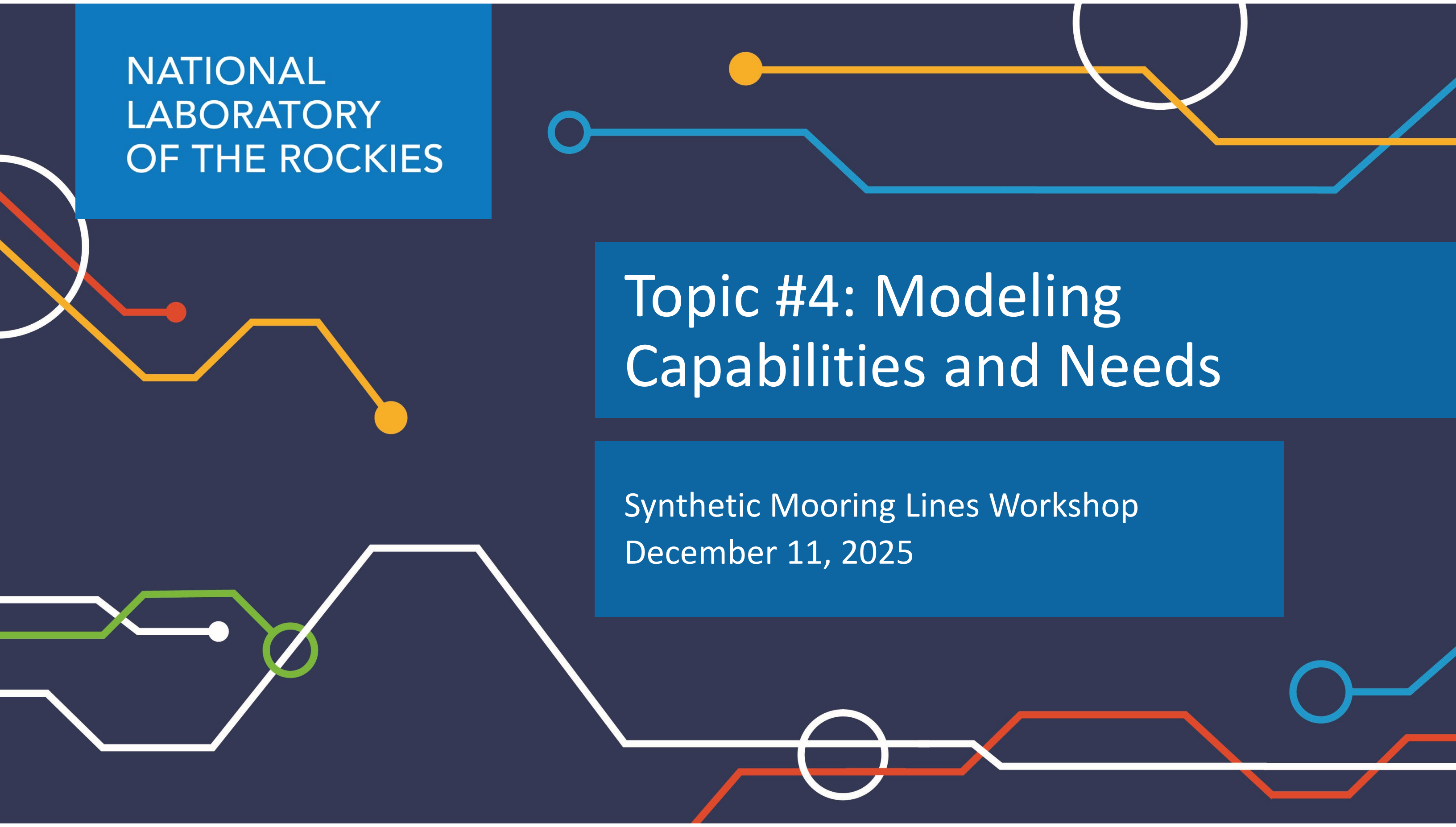
FUTURE DIRECTION

- Finding most appropriate test methods and analysis procedures for given test article properties, loading mechanism, deployment condition:
  - Standards and procedures from other industries, e.g. O&G, shipping
  - Mooring industry & technology developers

- Mooring testing campaigns, using field/numerical model boundary conditions as input

- Database for mooring testing results

Questions? Comments?
Contact: budi.gunawan@sandia.gov


NATIONAL
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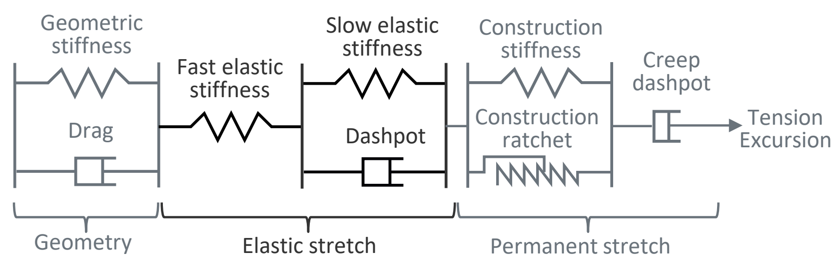
OF THE ROCKIES
Topic #4: Modeling
Capabilities and Needs
Synthetic Mooring Lines Workshop
December 11, 2025

Background

- Synthetic fiber rope mooring lines have many phenomena to model

- The current state of the art for fiber rope modeling is limited by data availability:
  - The Syrope JIP made the most well known approach for nonlinear fiber rope elasticity modeling, but its approach and data are not public.
  - [Nguyen and Sharman (Marine Structures, 2022)](#) developed the SYNCOM model. It is public, but widespread application requires fits to test data for each type of rope.



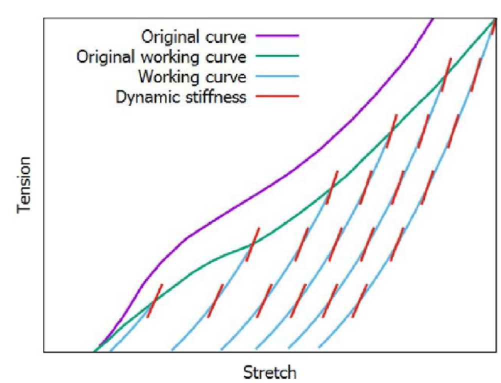
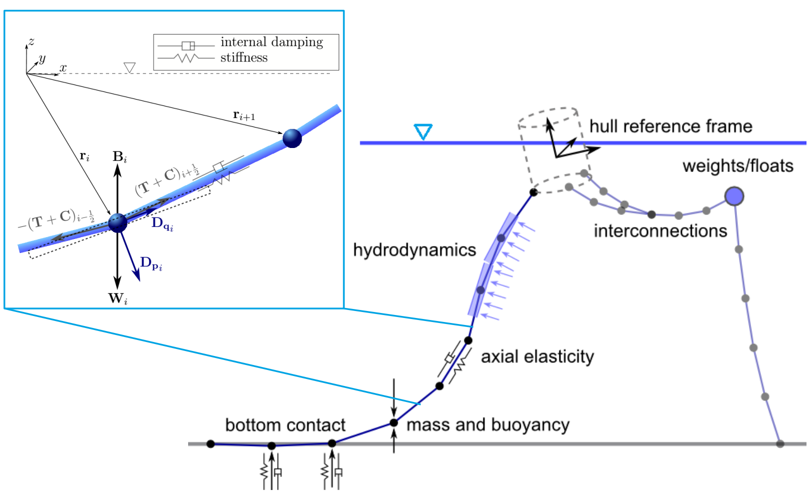


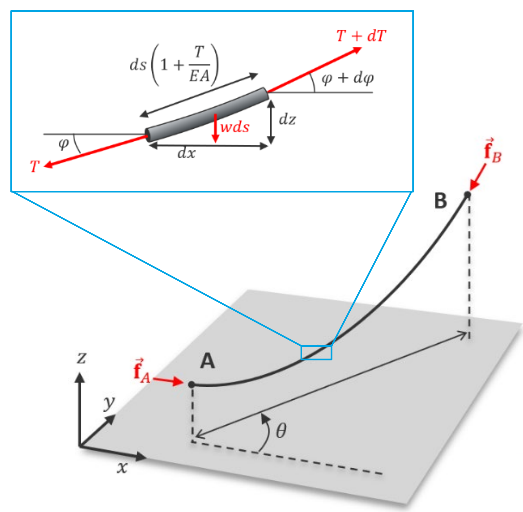
Illustration of the Syrope model from Falkenberg et al. (2019)

Background – Numerical Models

MoorDyn
A versatile, lumped-mass dynamic mooring model

MoorPy
A fast, quasi-static mooring model

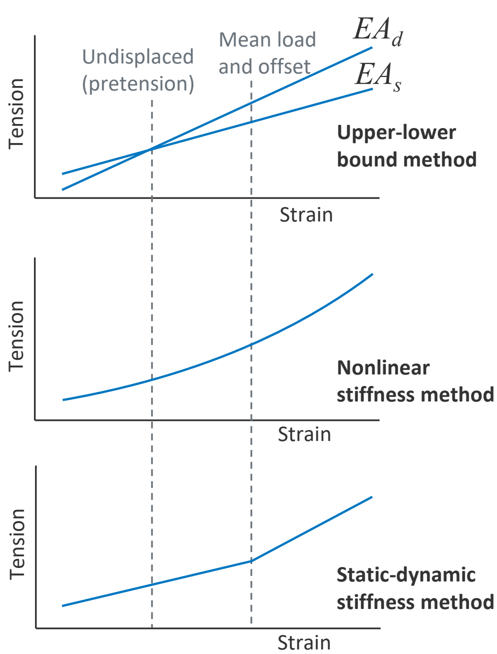


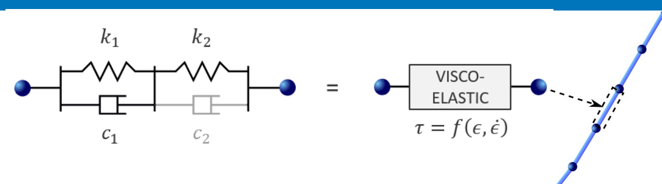


OrcaFlex
A commercial, robust software package for marine system analysis

Background – Recent Work on Rope Modeling

Surveyed the classical approaches

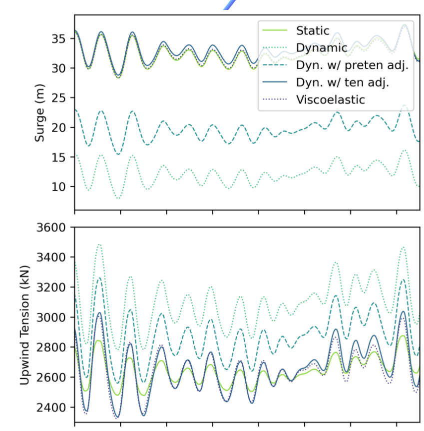




Comparison of five approaches:

- **Static**: uses the static stiffness value.
- **Dynamic**: uses the dynamic stiffness value without any adjustment.
- **Dynamic with pretension adjustment**: adjusts the line lengths to match the mooring system's undisplaced pretensions.
- **Dynamic with tension adjustment**: adjusts the line lengths to match the mean tension of each load case.
- **Viscoelastic**: accounts for both the static and dynamic stiffness throughout all load cases

Hall et al. (IOWTC, 2023)



Implemented a straightforward "viscoelastic" approach in MoorPy and MoorDyn that provides best of both worlds

Background – Recent Work on Rope Properties

- Updated NLR models to use three rope elasticity coefficients:

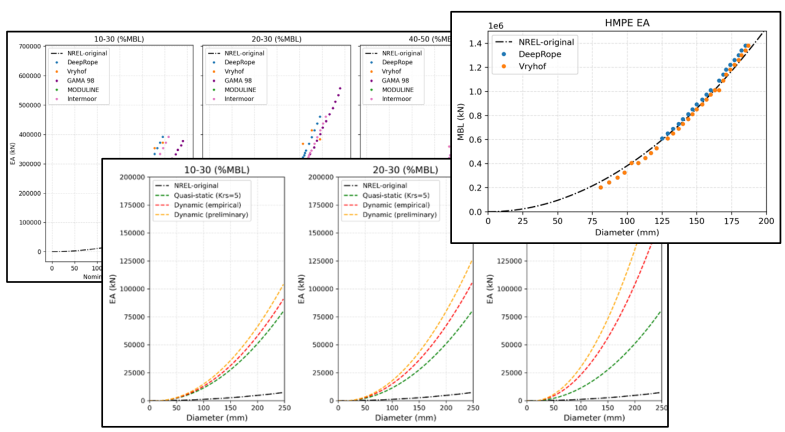
$$\boldsymbol{K_{rs}}$$

$$K_{rd} = \boldsymbol{\alpha} + \boldsymbol{\beta} L_m$$

- Generated reference coefficient scaling values for different mooring materials and sizes from catalogs, reports, and papers
- These “reference properties” provide public, representative assumptions but there can be considerable variation in actual rope products

TABLE 1: SELECTED MOORING LINE COEFFICIENTS

Coefficient	Polyester	Nylon	HMPE
m/d^2 (kg/m/m^2)	798	648	453
d_{vol}/d (-)	0.86	0.85	1.01
MBL$/d^2$ (MN/m^2)	170.5	164	619
k_{rs} (N/m^2)	14	5	56.5
$k_{rd}\alpha$ (N/m^2)	14	1	59
$k_{rd}\beta$ (N/m^2)	0.34	0.3	0.54



Outstanding Challenges

- Limited Model Capabilities
  - The widely used MoorDyn model has a *basic* viscoelastic implementation.
  - Several more advanced models existing in *proprietary* form.

- Lack of Standard Modeling/Characterization Approaches
  - A variety of approaches to synthetic rope modeling and characterization are used across manufacturers, researchers, and designers.

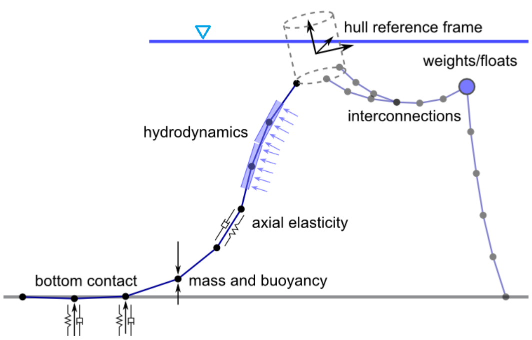
- Lack of Public Test Data
  - Advanced rope elasticity modeling requires fits to test data, and that data does not exist in the public domain.

Future Direction

- Limited Model Capabilities
  - ❑ Expand MoorDyn to implement state-of-the-art viscoelastic models, matching the fidelity of proprietary approaches.

- Lack of Standard Modeling/Characterization Approaches
  - ❑ Convene research, rope manufacturers, and system designers to agree on standard modeling approaches and parameter sets to use across applications.

- Lack of Public Test Data
  - ❑ Set up testing plans, facilities, and industry partners
  - ❑ Perform a large testing campaign across rope types and sizes
  - ❑ Process test results, fitting to standard model parameter sets
  - ❑ Publish data



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