Comprehensive Status Report: November 18, 2004

OTRC Project Title: Polyester Rope Analysis Tool
MMS Project 369   TO 17019
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MMS COTR: A. Konczvald

This report provides a comprehensive summary of the research completed in all prior Phases of this project (November 1999 – August 2004), and describes research being done in the present Phase (September 2004 – August 2005) to complete this project.

Polyester Rope Analysis Tool

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OBJECTIVE:

As exploration and production of petroleum moves to deeper waters, the use of steel mooring systems for floating structures becomes very expensive and introduces operational complexities. Steel mooring systems require a large anchor footprint and the need to support its large self-weight. Due to these limitations, alternative mooring systems are being sought to help reduce costs and improve efficiency. One alternative that has received a great deal of attention from the oil industry is the use of polyester rope in a taut mooring configuration. Of major concern, both to the oil industry and the Minerals Management Service (MMS), is that polyester taut mooring systems provide sufficient reliability and safety over an expected design life of 20-30 years.

To address these concerns, the primary goal of this research project is to ensure the availability of a validated software tool that can be used to predict the response of polyester ropes and their tolerance to damage under a variety of loading conditions. Such a tool is needed to interpret and extend test data and to develop design guidelines. Laboratory testing of large and full-scale ropes, while essential for gauging performance, is expensive and time consuming. Development of a reliable computer model has the potential to significantly reduce the costs and time needed for physical testing.

APPROACH:

In recent years, there has been an increasing amount of research activity investigating how polyester ropes behave in the marine environment. Test results have indicated a variety of different failure mechanisms that depend upon the nature of the applied loads as well as the characteristics of the test specimen. In addition, deformation characteristics have been shown to be a complex function of the magnitude of the applied loads, loading rate, and loading history. Because of the proprietary nature of many of the ongoing projects, and because of the great variability in rope types, test methods, and other factors, there are limited data available for developing a good understanding of how polyester ropes behave in response to general loading conditions. Furthermore, of the data that are available, there is concern that much of it is not consistent or reliable.

One source of detailed information on the behavior of synthetic-fiber ropes is the U.S. Naval Civil Engineering Laboratory (NCEL). Previous research sponsored by NCEL addressed both experimental testing as well as the development of a modeling tool called Gen-Rope. Development of Gen-Rope was conducted by Tension Technology Incorporated (TTI) of Preston, England. Because of the lack of reliable experimental data to validate the assumptions incorporated in the software, there are limits on the parameter space over which the program provides accurate results.

The general approach to the current research project was to focus initially on the review all previous literature and test data related to the response of synthetic-fiber ropes. In addition, different mechanisms that can lead to damage of a rope, which is a major concern for the long-term performance of these systems, were investigated. The Gen-Rope software was thoroughly evaluated to determine its suitability for modeling rope response when damage is present. It was concluded that the capability of Gen-Rope to model damaged synthetic-fiber ropes was limited, and these limitations could not be easily resolved through limited enhancements, modifications, or additions. Thus it was decided that a new software tool must be developed to simulate the response and residual strength of damaged rope. This research is resulting in a new software tool suited for modeling both intact and damaged polyester rope. This model also includes capabilities not found in Gen-Rope, and is being validated against a significant set of experimental data on undamaged and damaged rope.

PROJECT ACCOMPLISHMENTS FOR YEAR 1 (2000-2001):

Work Completed: The following tasks were completed in 2000-2001:

1. Acquired the Gen-Rope software and reviewed its usage and theoretical development.
2. Compiled available literature related to modeling of synthetic-fiber ropes.
3. Performed analyses with Gen-Rope and assessed its capabilities and limitations.
4. Acquired available test data.
5. Began the development of a new software tool.

Summary of Results: The following results were achieved in Year 1:

An early objective of the research that was completed during Year 1 was the evaluation of Gen-Rope's capability to model the response of polyester ropes under a variety of loading scenarios. For the purposes of the current project, it was essential that the software be able to represent several different types of rope construction. Rope manufacturing methods vary widely, and modeling software must be capable of correctly capturing the cross-sectional properties of a large number of different ropes.

In accord with the concerns of the MMS, particular emphasis was placed on determining whether or not Gen-Rope could model the response of damaged ropes. In order to make this assessment, a thorough review of the theoretical development and implementation of the software was conducted. During the early stages of this project, several months were invested in reviewing previous literature and evaluating the capabilities and limitations of Gen-Rope. Based on our findings and our understanding of the sponsor’s long-term goals for this project, a decision was reached in conjunction with the MMS to begin development of a new software tool rather than modifying Gen-Rope to achieve the desired capabilities. The new software being developed as part of the current research includes many of the fundamental assumptions on which Gen-Rope is based and which have been shown to provide good correlation to data obtained from tests done for the U.S. Navy. Major features of the new software include the ability to model the response of damaged ropes and the ability to define very general loading scenarios that compliment experimental studies being conducted by other researchers supported by the MMS. During Year 1, approximately 10,000 lines of software were written.

The work described above was conducted with extensive feedback from the MMS, representatives from the oil industry, and rope manufacturers. The PI attended the workshop entitled “Advanced Fibre Rope Technology” hosted by Tension Technology Incorporated (developers of the Gen-Rope software), visited with Marlow and Whitehill rope manufacturers, met with Chris Leech, Ph.D. (developer of Gen-Rope), and toured the testing facilities at the National Engineering Laboratory in Scotland.

PROJECT ACCOMPLISHMENTS FOR YEAR 2 (2001-2002):

Work Completed: The following tasks were completed in 2001-2002:

1. Continued development and validation of our computational model for representing the response of polyester rope under both static and cyclic loads.
2. Continued acquisition of test data.
3. Continued review of relevant literature.
4. Preliminary analysis results for the response of damaged ropes under monotonic loading.

Summary of Results: The following results were achieved in Year 2:

Work continued on the development of a software tool to model the behavior of polyester ropes under a variety of loading scenarios. Particular focus was given to structuring the software in such a way that analyses could be done to compare the computed results directly with data reported in the literature. In addition, several theoretical models were formulated to address the issues of propagation of damage following the failure of any component within a rope, deterioration of rope properties under static or cyclic loading, and "bedding-in" of components during a rope's initial response period.

A significant advancement made in the research during Year 2 was the development and implementation of a load-control methodology for analyzing rope behavior. This capability did not exist within Gen-Rope, and its incorporation into the software was of great importance for our model on damage propagation. Because Gen-Rope only allows for displacement control, a user is somewhat restricted in comparing computed output with measured test data as many tests on rope capacity are done using load-control. Aside from providing a user with greater flexibility in modeling rope response, the load control algorithm is essential for redistributing rope stresses from a failed component to the remainder of the intact rope. Thus, the incorporation of load control in the software marks an important step for characterizing the response of damaged ropes.

Over the course of Year 2, we continued to review the literature on modeling the response of ropes as well as gather data that is of relevance to the current work. By the end of Year 2, only a limited number of tests had been conducted on ropes that were damaged.

Researchers on this project were actively involved in several industry meetings and participated in several workshops, including the ASME-sponsored workshop on polyester moorings. Some early findings from the current research were presented at the 2002 ASCE Conference on Engineering Mechanics. The paper "Computational Model for Synthetic-Fiber Rope Response" by Rungamornrat, Beltran, and Williamson was accepted for publication in the conference proceedings. In this paper, parameter studies to demonstrate the capabilities of the new software were presented.

PROJECT ACCOMPLISHMENTS FOR YEAR 3 (2002-2003):

Work Completed: The following tasks were completed in 2002-2003:

1. Continued development and validation of our computational model for representing the response of damaged polyester rope under both static and cyclic loads.
2. Continued acquisition of test data.
3. Continued review of relevant literature.
4. Analysis results for the response of damaged ropes under monotonic loading.

Summary of Results: The following results were achieved in Year 3:

The numerical model to compute the impact of damage on the strength of polyester rope was used to analyze small-scale laboratory data of rope components made available from MMS-sponsored tests at the University of Houston's Composites Engineering and Applications Center (CEAC). Results have been encouraging. We have been able to show good correspondence between the values predicted by our computational model and the measured test data. The methodology used to calibrate the damage model is discussed in the paper "Degradation of Rope Properties under Increasing Monotonic Load." This paper was presented at the 2003 International Symposium on Deepwater Mooring Systems held in Houston in October 2003. A more general overview of the rope analysis software appears in the paper "Computational Model for the Analysis of Damaged Ropes", which was published in the 2003 ISOPE Proceedings.

In order to compute the response of a synthetic-fiber rope, a precise description of the geometry is necessary. Fig. 1 below identifies the typical components of a rope. By describing a typical component within the structure of a rope as being described by a helical geometry, and by further assuming that all components retain a helical structure following deformation under load, it is possible to develop the general equilibrium equations that define the response of a rope component. Furthermore, the analysis of an entire rope can be computed by assembling the response of each component in a hierarchical fashion. Thus, the base yarn response is used to determine the plyed yarn response, which in turn is used to compute the response of rope yarns, etc. (see Fig. 1).

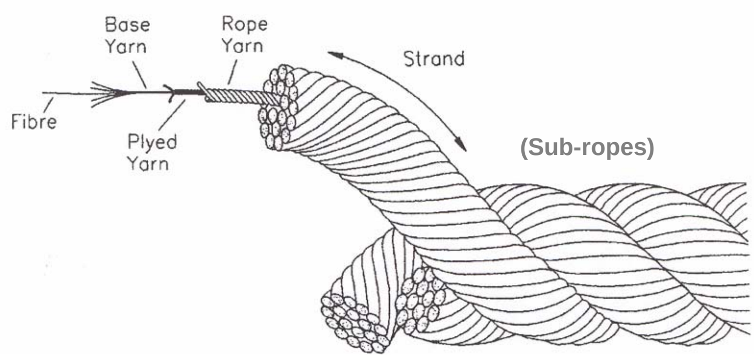

Fig. 1. Hierarchy ranking of rope components (Leech, 2002).

General equilibrium conditions for a helical component can be derived for general loading and deformation conditions. Fig. 2 illustrates a differential segment of a helical rope component with corresponding stress resultants (V_i and M_i). The contact forces and distributed moment per unit length, respectively, in the i direction are given by w_i and m_i. The general differential form of the equilibrium equations of a line element are developed considering an orthogonal local coordinate system. This system is formed by the tangent vector (x_1) that coincides with the longitudinal axis of the element; the normal vector (x_2) defined so that it is orthogonal to x_1 and oriented so it points toward the center of curvature of the element; and the binormal vector (x_3) defined to be perpendicular to the plane x_1 - x_2 such that x_1- x_2- x_3 forms a right-handed coordinate system (Fig. 2).

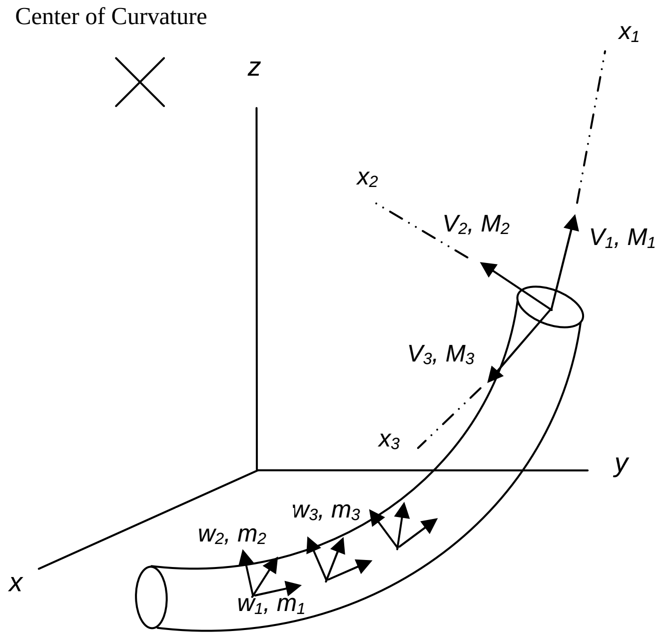

Fig. 2. Loads acting on a thin circular helix element.

In computing the response of a rope, two sources of nonlinearity must be taken into consideration. The governing geometry of deformation leads to equilibrium equations that are nonlinear in the geometrical parameters needed to define a rope. In addition, most synthetic fibers, including polyester, are best described by a nonlinear stress-strain law. Thus, both nonlinear geometry and nonlinear material properties lead to challenges in computing the final response.

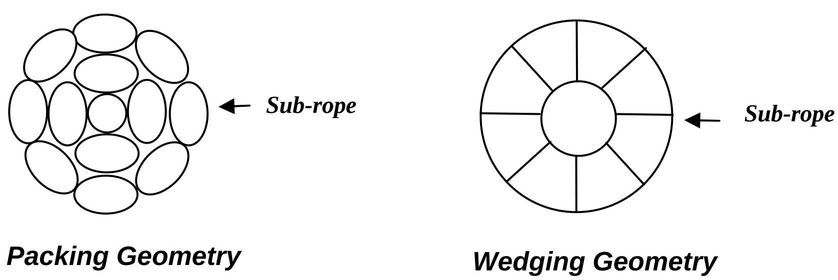

Fig. 3. Type of rope constructions.

Initial studies conducted with the computational model being developed for the current research showed excellent agreement with test data from small-scale ropes without damage. Many of the assumptions included in our model were validated, and the performance of the software was evaluated with parameter studies for a variety of rope geometries to study the effects that different rope constructions have on behavior. Unlike steel wire ropes, synthetic-fiber ropes experience significant cross-sectional deformations under response to load. Using the same methodology as employed in Gen-Rope, extremes in behavior to bound the response of cross-sectional behavior can be determined by considering *packing* geometry and *wedging* geometry. Graphical descriptions of these cross-sections are shown in Fig. 3.

For packing geometry, it is assumed that all components are initially straight and circular in cross-section, and a twist of a specified number of turns leads to the development of a helical structure. Contact between components in the same level is assumed to be only in the radial direction. In Fig. 3, the elements around the core appear elliptical in cross-section only because they make an angle (i.e., the helix angle) with the main axis of the rope body. Thus, when projected onto the cross-section, they do not appear circular even though they are.

For wedging geometry, the components in the same level are allowed to deform transversely and change their shape to a wedge or truncated wedge, which is the shape that would develop for deformable components. It is assumed that there is circumferential contact pressure and friction acting along the length of components due to axial slip between contiguous components. Radial contact, however, is assumed to be negligible in comparison to the circumferential contact and is ignored for computational purposes.

To extend the capabilities of the software beyond previous research, the ability to include the effects of damage was integrated into the computational model of rope response. The model is based on concepts from continuum damage mechanics that allow for a reduction in capacity as a function of different response variables. For the current study, we assumed damage to be a function of strain history, frictional effects, and number of load cycles at a given stress intensity.

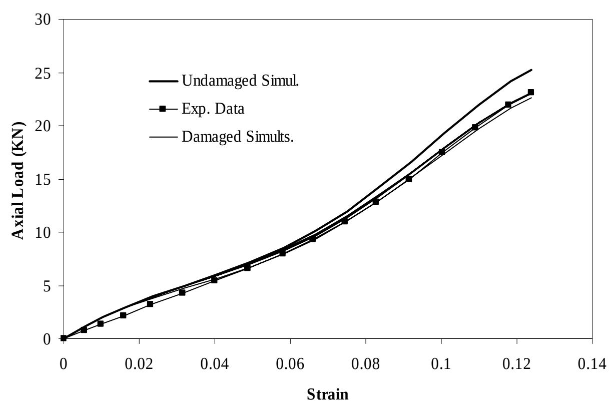

Fig. 4. Response of polyester strand under monotonic strain history: experimental, undamaged and damaged simulations curves.

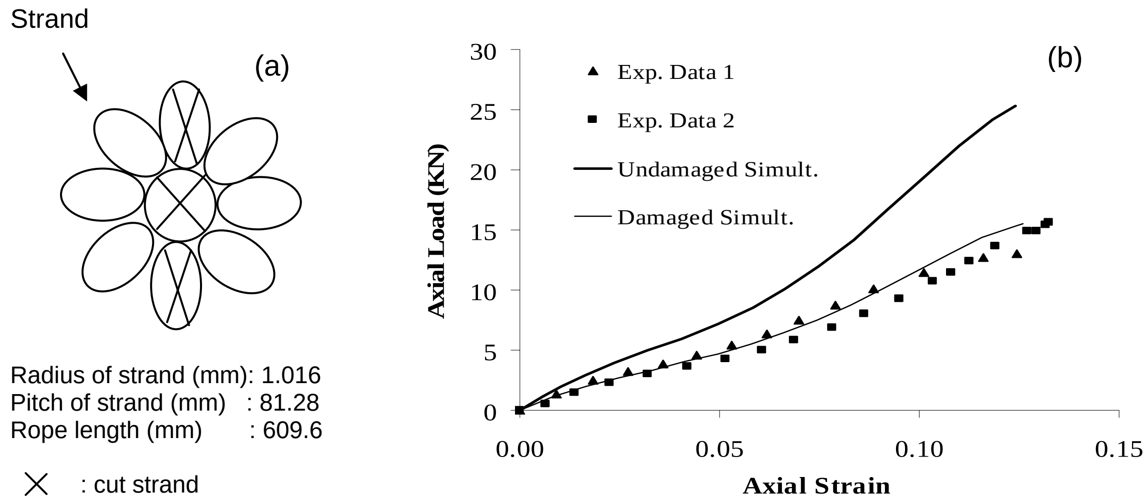

Fig. 5. (a) Cross-section and geometric parameters of damaged rope, (b) response of previously damaged rope under monotonic strain history: experimental, undamaged and damaged simulation curves.

To test the capabilities of the model, we modeled damaged rope components that were tested at CEAC. Some of the results of this evaluation are shown in Figs. 4 and 5. The graphs clearly show that the model we developed that accounts for damage does a much better job at predicting response than previous models that are not capable of accounting for the effects of damage. In Fig. 5, it is interesting to note the performance of the model. For this graph, results from damaged components at the rope-yarn level were used to predict the response of a strand. The results show that the concepts of using a hierarchical analytical procedure to compute rope response by assembling the effects at lower levels is a valid concept that leads to good predictions of behavior.

In addition to using test data to validate the computational models for predicting the behavior of damaged ropes, work performed during Year 3 extended the capabilities of the software to incorporate of a simple visco-elastic material model to represent the response of polyester. Prior to implementing a constitutive model that accounts for the effects of visco-elasticity, time-dependency was not accounted for in predicting rope response. The previous nonlinear material model was based upon empirical data and was very similar to the Gen-Rope model.

Over the course of Year 3, we continued to review the literature on modeling the response of ropes as well as gather data that was relevant to the current work. By the completion of Year 3, only results from small-scale tests on damaged ropes were available.

PROJECT PLAN FOR YEAR 4 (2003-2004):

Work Completed: The following tasks were completed in 2003-2004:

1. Continued development and validation of our computational model for representing the response of damaged polyester rope under both static and cyclic loads.
2. Continued acquisition of test data.
3. Verification of results using test data from other MMS-sponsored research.
4. Analysis results of small-scale length effect tests.
5. Support for the development of mitigation strategies and guidelines for polyester moorings damaged either in-service or during installation.

Summary of Results: The following results were achieved in Year 4:

Validation of the computational software to analyze damaged ropes using data from small-scale ropes tested at CEAC was completed. These data considered various levels of damage configured in a variety of different patterns. Some of the damage patterns were symmetric, while others were not. Predicted response from our computational models showed excellent agreement for all damage levels, particularly in the case where the damage pattern was symmetric around the cross-section. For unsymmetrical damage, the predicted results were still quite good. In addition to studying the results from these small-scale rope tests, analyses of large-scale ropes were initiated.

During Year 4, a test program organized through OTRC with funding from the MMS was started to address the effects of specimen length in affecting the measured response of different ropes. Results to date have shown a length effect, and work was undertaken to assess its importance. For some of the longer test specimens, experimental observations suggested a rope failure mechanism in which strain becomes localized around the site of initial damage. For shorter ropes, effects of termination efficiency make isolating this effect more difficult to characterize. Because the issue of strain localization was not identified in previous tests of shorter rope specimens, all previous computational models, including Gen-Rope and our new model, did not account for variation in properties over a rope length greater than a characteristic pitch distance. Measured results suggest that such an assumption to characterize the response of a mooring rope may not be accurate. Accordingly, in Year 4, we began working on extending our computational models to account for a variation in rope properties along the length so as to be able to account for the effects of strain and damage localization at the site of damage initiation. This work represented a major extension over previous computational models, and this effort was a major focus of our research.

Tests sponsored by the MMS and a JIP were conducted on 700 tonne damaged ropes, and these data are expected to become available in the near future. These tests results address issues related to length-effects and test scale. Some preliminary test results have been made available on 35 tonne ropes (much larger scale than those tested previously at CEAC). Initial predictions of rope capacity for partially damaged ropes have been made and compared with measured results. Fig. 6 shows the results for the case of a 35 tonne rope. In this figure, three measured capacities are provided, each corresponding to a different test specimen with a different length. In the legend, the location of failure in each specimen is indicated. The graph indicates reasonable accuracy in computing the breaking strength. The prediction of strain at failure, however, was not predicted as well. Further analysis of the data and test conditions, along with assumptions in the model, are being evaluated to determine ways in which to obtain better correspondence of the predicted and measured values. Issues related to splice efficiency and variability in the material properties, parameters that are not considered in our current computational model, will influence the results so that a precise match in measured versus predicted capacity is not likely to be achieved. However, it should be possible to obtain better correspondence on strain at failure than that shown by our initial predictions.

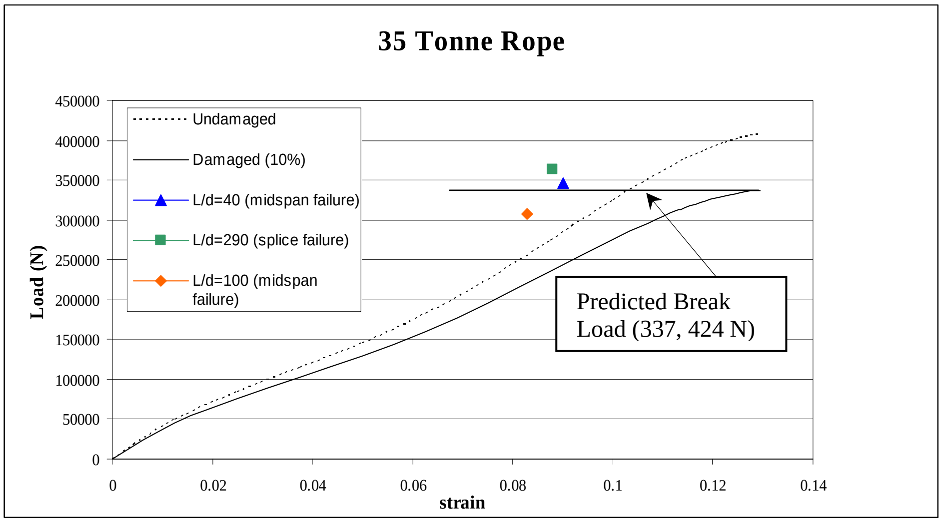

Fig. 6. Response of 35 Tonne Marlow rope — predictions compared to measured data.

Once all of the results from the large-scale tests are made available, analyses will be conducted to validate the numerical model's capability to predict the residual strength of damaged polyester rope. The model can then be used to support the development of recommended mitigation strategies and guidelines for polyester moorings damaged either in-service or during installation.

PROJECT PLAN FOR YEAR 5 (2004-2005):

Scope of Work: The following work is planned for 2004-2005:

1. Continued development and validation of our computational model for representing the response of damaged polyester rope under both static and cyclic loads.
2. Continued acquisition of test data.
3. Verification of results using test data from other MMS-sponsored research.

Anticipated Results: The following results are expected for Year 5:

1. Computational model that accounts for strain localization.
2. Analysis results of full-scale damaged ropes.
3. Support for the development of mitigation strategies and guidelines for polyester moorings damaged either in-service or during installation.
4. Documentation of analyses.

Year 5 is expected to be the final year of the project. During this time period, we will continue to develop our modeling software to help meet the overall project objective of ensuring the availability of a validated software tool that can be used to predict the response of polyester ropes under a variety of loading conditions. As data have become available and previously unrecognized aspects of rope response (e.g., strain localization) have been discovered, we have continued to enhance our program and modeling capabilities so that designers can have an effective tool in estimating the remaining life of a damaged polyester mooring.

REPORTS & PUBLICATIONS:

Currently, research efforts are focused on the development and refinement of a validated software tool for modeling polyester rope behavior. Listed below are the publications that have resulted from the research that has been completed to date. In addition to these publications, the PI and his students have made several presentations describing the ongoing research at a variety of workshops and conferences.

Rungamornrat, J., Beltran, J. F., and Williamson, E. B. (2002). "Computational Model for Synthetic Fiber Rope Response." Proceedings, Fifteenth Engineering Mechanics Conference, American Society of Civil Engineers, Columbia University, New York, NY, June 2-5, 2002.

Beltran, J. F, Rungamornrat, J., and Williamson, E. B. (2003). "Computational Model for the Analysis of Damaged Ropes." Proceedings, ISOPE (International Society of Offshore and Polar Engineers) 2003 Annual Meeting, Honolulu, HI, May 25-31, 2003.

Beltran, J. F. and Williamson, Eric. B. (2003). "Degradation of Rope Properties under Increasing Monotonic Load." Proceedings, 2003 International Symposium on Deepwater Mooring Systems: Concepts, Design, Analysis and Materials, American Society of Civil Engineers, Houston, TX, October 2-3, 2003.

Beltran, J. F. and Williamson, E. B. "Investigation of the Damage-Dependent Response of Mooring Ropes." Proceedings, ISOPE (International Society of Offshore and Polar Engineers) 2004 Annual Meeting, Toulon, France, May 22-28, 2004.

Beltran, J. F. and Williamson, Eric. B. "Degradation of Rope Properties under Increasing Monotonic Load." *Journal of Ocean Engineering* (accepted for publication June 10, 2004).