International Journal of Offshore and Polar Engineering (ISSN 1053-5381)
Copyright © by The International Society of Offshore and Polar Engineers
Vol. 36, No. 1, March 2026, pp. 32–39 ; https://doi.org/10.17736/ijope.2026.ar05

http://www.isope.org/publications

Simulating Material Hardening and Rate Dependencies in Subsea Cable Elements Using a Multi-linear Hysteresis Model

Kjetil André Karlsen-Husøy, Frank Woll and Jon Andreas Årstein
Technical Analyses Support, Nexans Norway AS
Halden, Norway

This study presents methodologies to simulate material hardening and rate-dependent behaviors in umbilical and subsea power cable elements using an earlier developed multi-linear hysteresis model. The model employs interpolation and boundary correction techniques to adapt the stress-strain response based on established principles of rate dependency and plasticity. Validation of the methodology demonstrates its ability to replicate expected material responses in the time domain. The findings highlight the model's versatility and its potential application in simulations to assess the structural integrity of subsea cable elements under complex loading conditions.

NOMENCLATURE

E	[MPa]	Young's modulus
E'	[MPa]	Interpolated Young's modulus
f_c	[Hz]	Cut off frequency
i	[-]	Time step index
j	[-]	Slope index
N	[-]	Cycles and cycle number
T_p	[s]	Peak period
t	[s]	Time
α	[-]	Kinematic contribution factor
$\bar{\alpha}$	[-]	Smoothing factor
ε	[-]	Strain
$\dot{\varepsilon}$	[s^{-1}]	Strain rate
$\dot{\varepsilon}_f$	[s^{-1}]	Dampened strain rate
ε_R	[-]	Strain reversal
ε_S	[-]	Significant strain height
ε_y	[-]	Strain at expanded yield limit
σ	[MPa]	Stress
σ_I	[MPa]	Isotropic stress
σ_K	[MPa]	Kinematic stress
σ_{KI}	[MPa]	Combined kinematic and isotropic stress
σ_L	[-]	Lower stress response boundary
σ_m	[MPa]	Adopted yield stress
σ_r	[-]	Response inside boundaries σ_L and σ_U
σ_U	[-]	Upper stress response boundary
σ_{xx}	[MPa]	Stress amplitude
σ_y	[MPa]	Yield stress
$\Delta\sigma_H$	[MPa]	Hardening stress range

INTRODUCTION

Umbilicals and subsea power cables are products that are built up by helically laid elements to transfer pressure, fluid, or electricity, increase strength, and isolate, monitor, or protect the product. Most of these elements can be treated as rate independent, i.e., the response is independent of the load application velocity. However, some of the materials are sensitive to the loading speed and some are also sensitive to thermal effects, which changes the response and adds an extra level of complexity in modeling their hysteresis behaviour.

These material phenomena and a phenomenon called strain hardening, which causes the yield stress to increase during plastic deformations, have been studied by several authors in the past and are often built on either a physically-based or a constitutive model that describes the material's stress-strain relationship (Yu et al., 2014; Zhu et al., 2016; Kubaschinski et al., 2022). The model can in turn be used in a FEM simulation to assess the risk of element failure (Zub et al., 2019; Kubaschinski et al., 2022; Shen et al., 2024).

The methodologies presented herein are based on a multi-linear model that was first presented in Karlsen (2021). The model allows for an efficient calculation of the hysteresis response directly from a given stress-strain relationship and a strain load. To capture the rate dependent response and the material hardening, an interpolation and a boundary correction process was introduced, which changes the stress-strain relationship according to established rate and plasticity principles.

The developed methodologies and essential parts of this work are detailed in this paper with a description of how the presented methods can be used to simulate the rate dependent response and the material hardening in umbilical and subsea power cable elements.

RATE INDEPENDENT MODEL

The multi-linear model, presented in Karlsen (2021), is used to simulate the rate independent response. The model requires a monotonic backbone curve defined in the 1st quadrant, as illustrated in the upper left in Fig. 1, to define the boundaries of the hysteresis response. It is presumed that a mirrored backbone curve over both the stress, σ, and strain, ε, axes applies to the compressional region in the 3rd quadrant. The curve in the 1st quadrant is processed into σ-ε curve parameters and linked to the load timeseries, $\varepsilon(t)$, in the multi-linear model, which returns the hysteresis.

The model performs well for materials with a backbone curve built up of decreasingly positive sectional slopes but performs moderately to very poorly for materials with fluctuating or negative slopes.

Received July 21, 2025; updated and further revised manuscript received by the editors September 22, 2025. The original version (prior to the final updated and revised manuscript) was presented at the Thirty-fifth International Ocean and Polar Engineering Conference (ISOPE-2025), Goyang/Seoul, Korea, June 1–6, 2025.
KEY WORDS: Multi-linear model, hysteresis material hardening, stress-strain, rate dependent, rate independent.