Construction and Building Materials 189 (2018) 1076–1092

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Mechanical properties of high strength steel strand at low temperatures: Tests and analysis

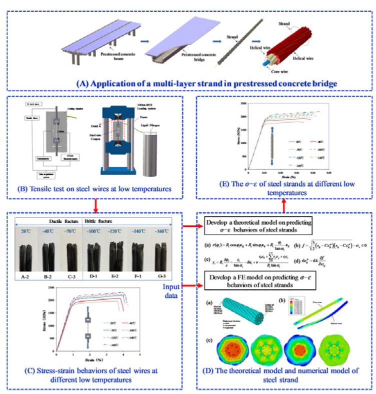
Jian Xie, Xueqi Zhao, Jia-Bao Yan *

School of Civil Engineering, Tianjin University, Tianjin 300350, China
Key Laboratory of Coast Civil Structure Safety of Ministry of Education, Tianjin University, Ministry of Education, Tianjin 300350, China

HIGHLIGHTS

- Low temperature of 20 to −160 °C increases strength but reduces ductility of steel wires.
- Proposed design equations predicts well strengths of wires at low temperatures.
- Theoretical models predict well nonlinear strength behaviours of steel strands.
- FE models simulate well stress-strain behaviours of strands at low temperatures.
- Proposed empirical equations offer means to determine strengths of strands at low temp.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 March 2018
Received in revised form 6 September 2018
Accepted 10 September 2018

Keywords:
Low temperatures
Steel strands
Prestress concrete structures
Concrete structures
Steel wires
Mechanical properties
Elastic-plastic behaviours
Finite element method

ABSTRACT

This manuscript studied mechanical properties of steel strands for prestressed concrete (PC) structures at different low temperatures ranging from 20 °C to −160 °C. 21 tensile tests were performed to obtain the stress-strain curves of steel wires in strand at different low temperatures. Empirical prediction formulae were developed to incorporate the influences of low temperatures on mechanical properties of steel wires. Based on the stress-strain curves of single wire, theoretical and numerical models were developed to predict the mechanical properties of multi-layer steel strands. The accuracies of these theoretical and numerical models were validated by the test results. Based on the test and analysis results, empirical models were developed to predict the mechanical properties of multi-layer steel strands at different low temperatures including the elastic modulus, yield and ultimate strengths. This offers useful means to calculate the mechanical properties of steel strands at low temperatures since their properties varied with their geometry and layout of steel wires. Finally, recommended prediction procedures are given to determine the mechanical properties of steel strands at different low temperatures.

1. Introduction

High strength steel strands are widely used in civil engineering constructions, e.g., prestressed concrete (PC) structures, long-span structures and bridges [1] as shown in Fig. 1. Due to their excellent mechanical properties, steel strands were also used in engineering constructions in harsh environments with low temperatures, e.g., infrastructures in cold regions, the Arctic onshore and offshore platforms, liquefied natural gas (LNG) containers. In northern China and Tibet, the recorded lowest temperature was −53.4 °C [2]. The lowest temperature in the Arctic could drop to about

* Corresponding author.
E-mail address: ceeyanj@163.com (J.-B. Yan).

https://doi.org/10.1016/j.conbuildmat.2018.09.053
0950-0618/

Nomenclature

A_0	cross sectional area of core wire	f_y, f_u	yield and ultimate strength of steel wire
A_i	cross sectional area of helical wires of layer *i*	f_{ys}, f_{us}	yield and ultimate strength of steel stand
E, E_1	elastic and plastic modulus of steel wire	$f_{ya}$$f_{ua}$	yield and ultimate strength of steel wire at ambient temperature
E_s	elastic modulus of steel strand	L	length of core wire
F_i	total axial force of helical wires of layer *i*	m_i	number of helical wires of layer *i*
F	total axial force of steel strand	r_0	radius of core wire
H_i	twisting moment in tangential direction of helical wires of layer *i*	r_i	radius of helical wires of layer *i*
I_E	factor for elastic modulus	s_i	length of helical wires length on the centreline of layer *i*
I_{f_u}	factor for ultimate strength	α_i	lay angle of helical wires of layer *i*
I_{f_y}	factor for yield strength	ε_0	axial strain of core wire
G_i	bending moment in binormal direction of helical wires of layer *i*	ε_i	axial strain of helical wires of layer *i*
N	number of steel wires in a strand	ε_y, ε_u, ε_F	yielding, ultimate and fracture strain of steel wire
N_i'	force in binormal direction of helical wires of layer *i*	ψ	cross-sectional area of steel wire
P_i	pitch length helical wires of layer *i*	φ_i	polar angle of helical wires of layer *i*
R_i	helix radius of steel strand	κ_i'	curvature in the binormal direction of helical wires of layer *i*
T	different temperature level		
T_0	ambient temperature	κ_i	curvature in the normal direction of helical wires of layer *i*
T_i	orce in tangential direction of helical wires of layer *i*	γ_i	torsional strain of helical wires of layer *i*
X_i	line load per unit length in normal direction of helical wires of layer i	χ_i	twists of helical wires of layer *i*
		v	Poisson's ratio of steel wire

−70 °C [3,4]. In the scenario of leakage of LNG, the external concrete structure of LNG containers may suffer low temperature of about −165 °C [5–6]. Since these infrastructures suffer low temperatures produced by these harsh environments, the mechanical properties of steel strands used in these structures at low temperatures need to be carefully considered for the evaluation on their structural performances.

There is extensive reported research on mechanical properties of steel materials at low temperatures. Elices et al. [7] reported tensile tests on hot rolled steel reinforcements at 20 °C, −80 °C and −180 °C. It showed that as the temperature decreased, both yield and ultimate strengths of steel reinforcements increased but their ductility was slightly affected. Lahlou et al. [8] studied the mechanical properties of mild steel at ambient temperature and low temperature −195 °C. The test results showed that strengths and elastic modulus increased but ductility significantly decreased at low temperatures. Yan et al. [9] carried out tensile tests on mild and high strength steel plates within temperature ranges of

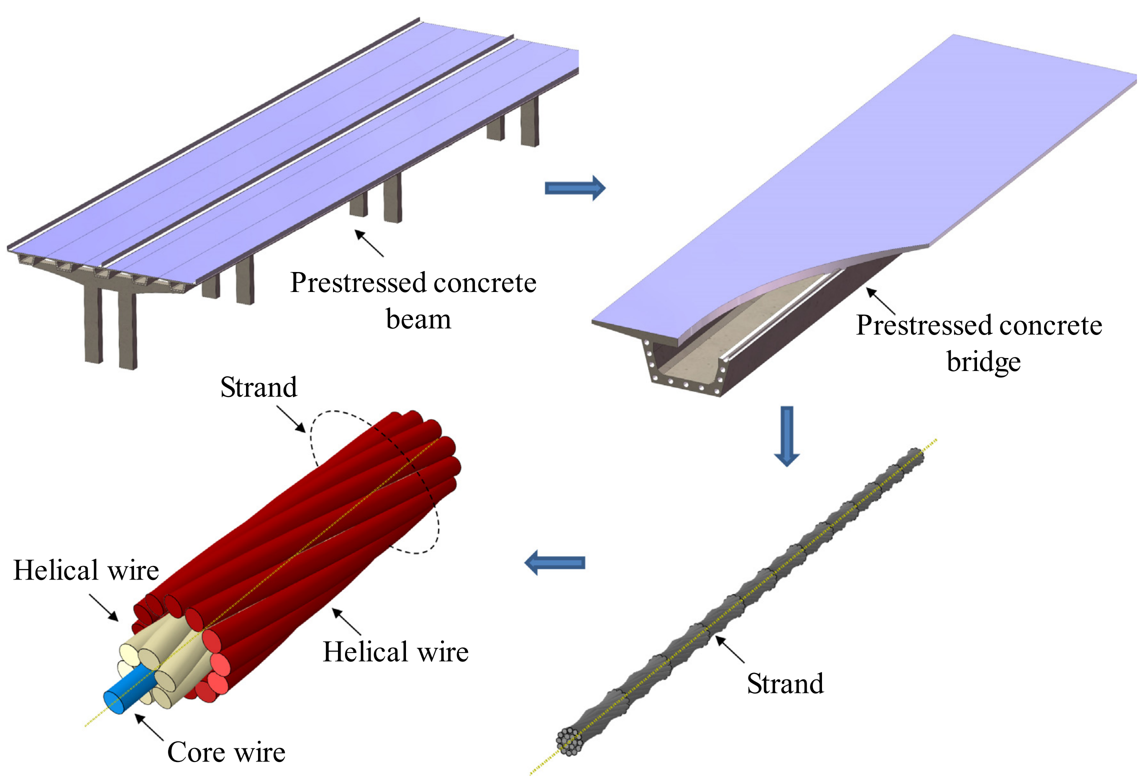


Fig. 1. The application of a multi-layer strand.