Construction and Building Materials 96 (2015) 279–288

Contents lists available at ScienceDirect

Construction and Building Materials

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

Experimental research on bending performance of structural cable

Zhihua Chen [a,b,c], Yujie Yu [c], Xiaodun Wang [b,c], Xiaofeng Wu [b], Hongbo Liu [a,b,c,*]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, China
[b] Key Laboratory of Coast Civil Structure Safety of China Ministry of Education, Tianjin University, China
[c] Department of Civil Engineering, Tianjin University, Tianjin, China

HIGHLIGHTS

- Quasi-static bending tests on semi-parallel wire cables, stranded ropes and steel spiral strands (Galfan) were performed.
- Different end conditions and the present and magnitude of pretension were considered.
- Bending behavior of cable was analogous to an elastic–plastic metallic beam.
- Welded end can add integrity to the cable but this strengthening effect is weak.
- Pretension can increase the cable flexural stiffness.

ARTICLE INFO

Article history:
Received 5 May 2015
Received in revised form 4 August 2015
Accepted 6 August 2015
Available online 13 August 2015

Keywords:
Cables
Bending test
Effective flexural stiffness
Pretension
Wire slip

ABSTRACT

Studies on bending properties of cables have long history but those researches are mainly around electrical conductors with very limit experimental discussions on structural cables. One approach on dynamic problems are through understanding changes in bending stiffness and utilized the varying bending rigidity into beam theory or beam finite element analysis. Therefore, a serial of quasi-static bending tests on semi-parallel wire cables, stranded ropes and steel spiral strands (Galfan) were performed to understand the cable bending response, with considering different factors like end conditions and the present and magnitude of pretension. The effective flexural stiffness of those structural cables were then determined and compared. Test results indicated that the unstressed cables under bending had an elastic–plastic like force–displacement response, which was analogous to an elastic–plastic metallic beam. Galfan strands showed better wire bounding behavior and cooperative bending due to different winding method. Welded end measurements can add integrity to the cable but this strengthening effect is weak and limited. Flexural response of the cable under a constant tension force was more like a linear relation with sag deflection. Pretension can increase the cable flexural stiffness, and this strengthening effect increased with the pretension level but decrease with the cable dimension. A simplified evaluation method of effective flexural stiffness was also proposed.

1. Introduction

Cables made of helically wrapped wires often act as structural elements in different structure fields like semi-parallel wire cables in bridges, strands in cable-supported structures, wire ropes in conveyance and conductor cables in electrical substations and transmission lines. Constructions of cable are usually made of a straight core and several layers of spirally wrapped wires with synclastic or alternate lay angles, which determines an extremely complicated mechanical behavior. However, since the general slender and intension application in practical bridges or cable-supported structures, cables are often regarded as rods or guys with a constant flexural stiffness and no compression resistance. But this assumption is not always reasonable, especially for large diameter spiral strands or comparative short cables. In those cables, the influence of bending stiffness will rise to a non-ignorable level, especially in dynamic response problems like vibration or frequency-based cable force evaluation [1,2]. Like a case study on Tsing Ma Bridge, the natural frequencies of main cable were compared to the computed frequencies with and without considering cable bending stiffness, results showed that ignoring bending stiffness gives rise to unacceptable errors in predicting higher order natural frequencies of the cables [3].

* Corresponding author at: Department of Civil Engineering, Tianjin University, Tianjin, China.

E-mail address: hbliu@tju.edu.cn (H. Liu).

http://dx.doi.org/10.1016/j.conbuildmat.2015.08.026
0950-0618/

The most important dynamical property of cable is wire slippage that creates large variations in flexural rigidity, that the bending stiffness varies between two limits: the maximum rigidity on wire fully stick state that no wire slip or relative motions are allowed, and the minimum stiffness for cables that all the inside wires act independently and are free from each other to move [4]. While since the bending stiffness changes with the bending amplitude and loading history, and maximum and minimum bending stiffness values may differ by several orders of magnitude, the uncertainty about the bending stiffness is still a tackle in cable studies, especially dynamic properties [5–7].

On the cable vibration and damping studies, an appropriate cable model that can describe the bending stiffness and damping properties determines a reasonable result. Cables were initially modeled as a string in tension with negligible bending and torsional stiffness [8,9]. Then the influence of cable geometry and bending characteristics prompted a thin rod model that incorporated bending and torsion by modelling the individual wires as thin rods, but the interaction between the wires were often assumed to be frictionless [10–12]. However, latter studies found that thin rod theory was more suitable for small diameter strand, then another homogeneous (semi continuous) model came out, in which each helical wire layer is simplified as a cylinder, then the friction and damping effect were assumed to happen between adjacent cylinders or wire layers [13,14].

Another approach on dynamic problems are through understanding changes in bending stiffness and utilized the varying bending rigidity into beam theory or beam finite element analysis. Then the first step is to understand the wire motion and slipping propagation during bending, and these can be studied through theory deviation or experimental observation. Papailiou [4,15] modeled a cable damping from the studying the interwire frictional contact under bending and then formulated a relation between flexural stiffness and bending curvature. He also conducted two Aluminum Conductor Steel Reinforced (ACSR) conductor bending tests with different wire compositions and lengths to validate the proposed theory. Later Hong [16] and Cardou [17] extended Papailiou's work and made improvements on describing the varying bending stiffness of bent cable. Filiatrault [18] also conducted quasi-static bending tests on two different flexible conductors to find the flexural stiffness and hysteresis behaviors. With the relation between bending curvature and flexural stiffness, cable damping with inter wire friction can then be studied by using beam elements. Dastous [19] worked out a tangent stiffness with discrete flexural rigidity and developed a beam element with varying bending stiffness to simulate cable behavior under different loading or damping conditions. Knapp also explored varying flexural stiffness through wire slip test and then incorporated the flexural rigidity curvature into cable damping and vibrations [14].

Detailed researching history on cables can be found in review studies [6,20] and results reveal that cable bending and damping properties are greatly influenced by interwire friction. But among all those approaches, modelling the variability in bending stiffness may be a straightforward way to include damping in cable modelling [21]. However, despite those previous experimental explorations and theoretical models, those research subjects were mainly electrical conductors, with very limit discussions on structural cables. Generally used structural cables includes steel spiral strand with wire diameters usually as 5 or 7 mm, and semi-parallel wire cables and stranded ropes which are widely used in structures and bridges. Although with similar construction patterns, the electrical conductors are usually made up of aluminum and small diameter wires, but the cables use steel instead. Moreover, the electrical conductors only have alternative winding construction with lay angle range usually in 10–15°, while cables used in buildings and bridges have many fabrication methods. Like wires in semi-parallel wire cables are slightly twisted concurrently with only 2–5° lay angle.

Structural cables usually process large dimension that are hard for lab testing. Besides the opportunities for onsite testing of bridge cables are precious and testing results are easily being influenced by the structural vibrations. Then researches on damping behavior of structural cables are mainly through theoretical derivations or numerical simulations with dramatic simplifications on bending stiffness or damping properties [1,22,23]. And there are not many experimental data for structural cable bending, especially for large dimension ones. Similar to bending researching of electrical conductors, understanding the bending behavior of structural cables can also help the further study of damping or vibration behaviors in structural engineering. Then this study conducted a serial of exploring quasi-static bending tests on structural cables (semi-parallel wire cables, stranded ropes and steel spiral strands (Galfan)). Axial tension force were considered in the experiments and three different pretension levels were selected and compared with unstressed conditions. Based on test data and previous studies on strand conductors, an effective flexural stiffness relation of structural cables are calibrated, which describes the relation of bending rigidity to lateral deflection and cable force. The proposed effective flexural is based on beam theory hence the relation can be incorporated into beam modelling for structural cables to study the overall cable performance like the frequency-based force evaluation and vibration response.

2. Bending test design of cable

Here we define three flexural stiffness: EI_{max} is the moment inertia of the cross section as a single solid; EI_{min} represents the sum of flexural rigidity of each wire, and EI_{eff} is the effective flexural stiffness that obtained from the experimental results. Here we can add a coefficient k as the influencing factor, which ensure the relation below:

$$EI_{eff} = kEI_{min} \tag{1}$$

Therefore the aim of bending tests comes to understand the changing trend of EI_{slip}, and to obtain values of this influencing factor k. The experimental setup and key compositions for the quasi-static cable bending tests are shown in Fig. 1(a) and (b). The tests here adopted the free bending phase in which the cable bending was ensured by applying a transverse load in its mid-span. Then the cable was free to expand its curvature around the point where the force was introduced. Simple supports were installed that enable the cable ends' freely rotation, and due to the round section geometry, specially designed supporting pads with different size were used in the tests, as shown in Fig. 1(c). Totally five dial indicators were arranged at the mid-span, quarter span and simple support locations to measure the sag displacement, as shown in Fig. 1(d). Since the tests adopted force-loading method and previous reviews indicate that the cable's bending and deforming is an elastic–plastic like process, those displacement measurements are collected at the stabilized state during each loading step.

All those cable specimens in the test were 1050 mm long and the distance between two supporting pads was 820 mm, which was also the bending span. Three most generally used structural cable types were tested here: stranded rope, semi-parallel wire strand and steel spiral strand (Fig. 2). The number of specimens tested in different conditions are listed in Table 1. The experimental factors include cable dimension, cable style, end condition of cable, and the presence and magnitude of pretension. Then to realize this comparison, totally 77 cable specimens were tested here.

The effective flexural stiffness is made up of elastic stiffness and geometry stiffness from force equilibrium. Moreover, in pre-