Engineering Structures 86 (2015) 84–98

Contents lists available at ScienceDirect

Engineering Structures

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

Assessment of static rope behavior with asymmetric damage distribution

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ARTICLE INFO

Article history:
Received 8 February 2014
Revised 7 November 2014
Accepted 12 December 2014
Available online 12 January 2015

Keywords:
Damaged synthetic-fiber rope
Analytical model
Rope failure
Asymmetric damage

ABSTRACT

In this paper, a mechanical model is proposed to estimate the static response (stiffness, residual capacity, deformed configuration, strain/strain distribution within cross-section, and deformation capacity) of a rope asymmetrically damaged. In this study, damage corresponds to the complete rupture of one or more rope components in a particular rope cross-section location. In the proposed model, the damaged rope is assumed to behave as a nonlinear beam under biaxial bending and axial load with Bernoulli's kinematic hypothesis. Biaxial bending arises from the unbalanced radial contact forces within rope cross-section, which are related to the initial helical geometry configuration of the rope components, due to the asymmetric damage distribution. An efficient and robust iterative cross-sectional numerical algorithm is implemented to estimate the asymmetric damaged rope capacity curve, stress and strain distributions throughout rope cross-section and rope geometry deformation for a prescribed axial displacement of the rope. The results given by the proposed model are found to be in good agreement with available static tension tests on asymmetrically damaged small-scale (ropes diameter equal to 6 mm) polyester ropes and their corresponding 3D finite element (FE) simulations with lower computational cost. Additionally, compared to the solutions obtained by previous analytical models reported in the literature, the range of applicability associated to the degree of damage to rope cross-section (number of broken rope components) is extended.

1. Introduction

Ropes are employed in many engineering applications including cranes, lifts, mine hoisting, bridges, cableways, electrical conductors, offshore mooring systems and so on. This wide range of usage demands ropes manufactures to provide different configurations of ropes suited for different purposes, having a different number and arrangement of rope components within the rope cross-section, and rope components can be made of different materials such as metal, natural and synthetic fibers [1,2].

Mechanical demands, abrasion, and environmental interaction (corrosion, ultra-violet light, chemical, and heat exposures, etc.) degrade the properties of the individual rope components continuously during rope operational service. This degradation process, that represents how damage in a rope evolves, could result in the complete rupture of one of more rope component and eventually will lead to rope failure. Damage to ropes, which could start during rope transportation and installation, is complex and different for each rope application, revealing the local operating parameters and the characteristics of the rope selected [3].

The understanding of the interaction of the factors that induce damage to rope and their dependence on the rope operational conditions are essential to estimate rope service life at the design stage and to establish the appropriate rope inspection methods and discard criteria. Hence, the service life of a rope can be greatly extended by following a planned program of installation, operation, maintenance, and inspection [3]. In this context, damage-tolerance property (i.e., the ability of a rope to withstand damage), is an essential parameter for rope design, rope evaluation during operational service, and for developing discard criteria according to rope usage based on the residual strength and deformation capacity that the damaged rope can sustain.

Several experimental [4–12] and theoretical [13–18] studies have shown that the impact of the presence of broken rope components on overall rope response (stiffness, residual strength and deformation capacity) depends on the length of the rope, number of broken rope components (degree of damage) and their distributions throughout rope cross-section (symmetric and asymmetric)

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http://dx.doi.org/10.1016/j.engstruct.2014.12.026
0141-0296/

and along the rope length, and rope construction. These studies have mainly been conducted on steel wire ropes and synthetic fiber ropes. In particular, if the rope length, type of rope construction, and location of the damaged cross-section are fixed, above studies conclude that the effect of rope components breaks on rope response is not always directly proportional to the equivalent loss of cross-sectional area (the so-called net area effect) and asymmetric damage distribution induces a lateral displacement of the rope and a non-uniform strain (and stress) distribution throughout rope cross-section, resulting in premature failure (deformation capacity) of the asymmetrically damaged rope relative to the intact rope. In addition, depending on the location of the broken components throughout damaged cross-section (inner or outer cross-section layers) potential strain localization around the failure region can develop due to the contact interaction among the unbroken and broken rope components, and as a result, a weaken cross-section acts over a localized region. The existence of this weaken cross-section can also cause the premature failure of rope components and reduce the rope failure strain and the maximum load a damaged rope is capable of resisting.

In this paper a simply mechanical model is proposed to estimate the deformed configuration, stress–strain distribution within cross-section and the capacity curve of an asymmetrically damaged rope subjected to axisymmetric loading conditions. This model assumes that an asymmetrically damaged rope behaves as a nonlinear beam under biaxial bending and axial load with Bernoulli's kinematic hypothesis neglecting the potential incremental contribution of broken rope components to overall rope response due to frictional forces (strain localization around the failure region effect) [16]. Comparisons with available static tension tests on asymmetrically damaged small-scale (ropes diameter equal to 6 mm) polyester (PET) ropes [10], previous analytical model reported in the literature [13,15], and 3D finite element (FE) simulations [18] are performed to validate the proposed model.

2. Numerical and analytical models

In this section, the main results presented in [18] are summarized in which 3D FE simulations (numerical models) were carried out to estimate the effect of asymmetric damage distribution to rope cross-section on rope response. The conclusions of these numerical simulations were used as the basis for developing a simplified and computational less expensive analytical model that allows predicting static behavior of asymmetric damaged rope, motivated by the computationally intensive 3D FE simulations. The formulation of this analytical model is presented in detail in this section.

2.1. Motivation: numerical models (FE simulations)

Beltran and Vargas [18] developed 3D FE models using the commercial software ANSYS for a particular PET rope component construction (hereafter referred as ropes) tested to failure (static capacity test) by Li et al. [10]: 6 mm diameter rope comprised of eight helical components (second layer of the rope) wound around a straight core (first layer of the rope), with initial pitch distance p_0 and helix angle θ_0 (angle between the longitudinal axis of the rope and local axis of the rope components) equal to 81 mm and 9.5° respectively. For modeling purpose, tested ropes geometry has one hierarchical structure identified (helical components wound around a central straight core) which defines the *level* of the rope geometry which in this case is one (i.e. one-level rope). These one-level two-layer ropes had initial lengths (L_0) equal to 610 mm (approximately 8p) and they were damaged prior loading by cutting a prescribed number of rope components (degree of damage) at ropes midspan that were distributed symmetrically and asymmetrically within rope cross-sections.

The boundary conditions of each 3D FE model considered one end section of the rope fully clamped and at the other end an axial displacement history is specified and the cross-section is prevented from rotating. For the particular case of asymmetrically damaged ropes, 3D FE simulations demonstrated that these ropes deflect laterally inducing a non-uniform axial strain distribution throughout rope cross-sections and a reduction in their residual strengths and deformation capacities relative to the net area effect concept (model that just neglects the contribution to rope response of the broken components). In order to illustrate the above general conclusions (details can be found in [18]), the deformed configuration and axial strain (natural strain) distribution throughout rope cross-section and along the rope length for the rope W_{12} given by 3D FE simulations are depicted in Fig. 1. The notation used to identify a particular cross-section is as follows: W_{ij} where W refers to the cross-section and the indices i and j refer to the broken rope components (i and j vary from 0 to 9) based on the undamaged rope cross-section (W_u) also shown in the figure (Fig. 1a and b). The degree of asymmetry of the cross-section is quantified by a scalar quantity termed the index of asymmetry (*IA*), which captures the shift of the center of stiffness of the rope cross-section from its centroid due to the asymmetry of damage distribution as explained in Appendix A [18]. As the values of the parameter *IA* vary in a nonlinear fashion with respect to the rope axial strain due to the nonlinearity of the constitutive law of the PET rope components, its initial value, $(IA)_0$, is considered as a representative measure of the degree of asymmetry of the rope cross-section as discussed in [18].

To be consistent with previous researchers [10,11,17,18], measured and predicted damaged rope axial load-axial strain curves are plotted up to the maximum load and its corresponding strain, that represent the onset of damaged rope failure in which the subsequent fracture process of the rope cross-section is not part of this study. Consequently, these pairs of data are assumed to be the failure axial loads and failure axial strains of the analyzed ropes. This assumption is supported by several experimental and analytical research studies available in the literature ([11,19–22]) that conclude that after the rope reaches its maximum tensile, it experiences softening in a very small region of the plane axial load–strain in comparison to the region that the rope develops its maximum capacity.

Based on the results shown in Fig. 1c, the maximum axial strains are developed in the adjacent rope components to broken components (shown in gray color) and the minimum values are developed in the opposite rope components. Based on the conclusions drawn in [18], the gradient of the axial strain distribution throughout damaged rope cross-section increases as the $(IA)_0$ (hereafter referred as *IA*) value gets larger, in which the ratios between the maximum and minimum strain values at the onset of ropes failure, for example, are 1.15, 1.20 and 1.30 for ropes W_1, W_{12} (shown in Fig. 1c), and W_{1234}, respectively. As a reference, this ratio value for the case of an initially undamaged rope (W_u) is 1.11. Consequently, due to the increasing gradient in the axial strain distribution, an increasing additional reduction of the residual strength relative to the net area effect (reduction in rope strength is proportional to the loss of cross-sectional area) occurs while the deformation rope capacity (failure strain) decreases compared to the intact rope value: maximum additional reduction of the residual strength is close to 10% for rope W_{1234}; and for the same rope, 7% in reduction of failure axial strain value relative to the intact rope (Table 1).

For the particular rope construction studied in [18], unbroken rope components of an asymmetric damaged rope develop constant axial strain values along the ropes lengths which suggests