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Vulnerability and failure analysis of hybrid cable-stayed suspension bridges subjected to damage mechanisms

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ABSTRACT

A numerical model for considering the damage and failure behavior on the cable system is proposed, which can be utilized for obtaining the response of hybrid cable-stayed suspension bridges subjected to moving loads. Damage and failure phenomena on the cable system elements, produced by preexisting corrosion phenomena or unexpected failure mechanisms, are analyzed by using stationary or time dependent explicit laws, developed in the framework of the Continuum Damage Mechanics theory. The bridge analysis is developed by using a refined FE nonlinear geometric formulation, in which the effects of local vibrations on the cable-stayed and suspension systems as well as the influence of large displacements in the girder and the pylons are taken into account. Particular attention is devoted to evaluate the initial configuration under self-weight loads and the corresponding cable dimensioning, which is achieved by solving a constrained optimization problem. Parametric studies are conducted with the purpose of investigating the vulnerability of the structure against damage and complete failure phenomena produced in the cable system by means of comparisons between damaged and undamaged bridge configurations.

1. Introduction

Over the past decades, cable supported bridges have been frequently adopted owing to their ability to overcome long spans, to the reduced costs involved in the bridge construction and to aesthetic reasons because of their enhanced geometric configurations. However, such structures are typically exposed to several damage mechanisms, which lead to a progressive material degradation of the bridge components [1,2]. Therefore, in order to verify the performance of the structure, it is necessary to investigate the effects on bridge behavior of such damage phenomena by considering both serviceability and ultimate working conditions. Regarding design, existing codes on cable supported bridges recommend verifications of the robustness and the vulnerability of the bridge with respect to accidental loading conditions. They reproduce specific loading schemes in which the cable system is affected by internal damage mechanisms [3,4]. Moreover, dynamic non-destructive methods aimed at a proper assessment of the bridge integrity are based on suitable procedures, which identify the presence of damage phenomena in the structure by means of comparative studies between the experimental data recorded in the bridge with the ones predicted by using a specialized structural modeling [5,6]. Consequently, the complete identification

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Nomenclature

$(\cdot)^G$	stiffening girder variable
$(\cdot)^P$	pylon variable
$(\cdot)^C$	cable system variable
$(\cdot)^m$	moving mass variable
$(\cdot)^0$	variables associated to the initial configuration
A_i^S	cross sectional area of main cable
A^G	girder cross sectional area
A^P	pylon cross sectional area
A_i^S	stay cross sectional area of the i-th cable
A_0^S	anchor stay cross sectional area
b	half girder cross section width
c	moving system speed
$C^{G,P}$	elasticity modulus of the girder (G) or of the pylon (P)
C^C	cable elastic modulus
CE	constraint equation
e	eccentricity of the moving loads with respect to the girder geometric axis
E_1	Green–Lagrange strain
H	pylon height
I_i	moment of inertia with respect to the i axis
I_{0i}	polar moment of inertia around the i axis
J_t	factor torsional stiffness
l	lateral bridge span
L	central bridge span
L_0	development of the cable element
L_p	length of the moving loads
L_T	total length of the girder
m	exponential coefficient of the damage function
M_{0i}^G	limit elastic bending moment of the girder along i-th axis
M_{0i}^P	limit elastic bending moment of the pylon along i-th axis
N_0^G	limit elastic normal stress resultant of the girder
p	live loads
S_g	design stay stress under self-weight loading
S_a	allowable stay stress
S_1	Piola–Kirchhoff stress
$SNOPT$	Sparse Nonlinear OPTimize
U_i	component of the displacement field along i – axis
t_0	starting time of the damage mechanism
t_f	duration of the failure mechanism
α	relative position of the damage region
β	extent of the damage region
Δ	stay spacing step
γ	stay specific weight
λ_{ML}	moving load mass per unit length
λ_{ML}^0	torsional polar mass moment of moving load per unit length
μ^C	stay mass per unit length
μ^G	girder self-weight per unit length
ξ_d	static value of the damage variable
ξ_d	dynamic function of the damage variable
Ψ_i	component of the rotation field around i axis

of the damage effects or the evaluation of the structural behavior of cable structures, subjected to unexpected damage mechanisms, are considered to be important tasks, in health monitoring for the maintenance and rehabilitation of older structures or in the design procedure for the analysis of new ones.

In the literature, damage analyses are mainly developed on a single cable or simplified cable systems involving a preexisting inelastic region in the cable development. In particular damage behavior of elastic suspended cables or cable-stayed beams is analyzed by means of closed form expressions or numerical approaches, in which the effects of diffused inelastic damage modes are investigated in terms of intensity and location along the cable development [7,8]. The results proposed by