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Wire rope isolators for seismically base-isolated lightweight structures: Experimental characterization and mathematical modeling

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ABSTRACT

The results of an extensive series of dynamic and static experimental tests conducted on four Wire Rope Isolators (WRIs) under different values of vertical load are presented. The main aim of this work is identifying the mechanical characteristics of WRIs in three displacements ranges, that is, small, relatively large and large displacements ranges, to allow the use of these metal devices in the base isolation system of seismically base-isolated lightweight structures. In order to simulate the dynamic behavior of WRIs in the two principal horizontal directions, namely, Roll and Shear directions, a one dimensional (1d) Nonlinear Exponential Model, able to simulate the increase of the tangent stiffness observed at larger displacements, is proposed. Compared to the widely used Bouc-Wen model, the proposed one does not require the numerical solution of a first order ordinary nonlinear differential equation, thus decreasing the computational effort of nonlinear time history analyses, and contains a smaller number of parameters to be identified. The mathematical model has been validated by comparing the experimental hysteresis loops obtained during cyclic tests with those predicted analytically.

1. Introduction

Wire Rope Isolators (WRIs) are metal devices that have demonstrated to be effective in protecting sensitive equipment from shock and vibration and have been originally used in numerous military, electronic and air space applications [1]. All the different types of WRIs, such as helical, arch or spherical devices, are made of two basic elements: a stainless steel cable and two aluminum alloy or steel retainer bars where the cable is embedded.

As far as the use of WRIs as seismic devices is concerned, Demetriades et al. [2] showed that an isolation system including stiff WRIs can reduce the acceleration transmitted to light but costly equipment allowing very small displacements in contrast to the classical base isolation approach of increasing the fundamental natural period of the system. Di Donna and Serino [3] and Serino et al. [4,5] investigated the use of WRIs for the seismic protection of circuit breakers of a transformation open-air substation, thus concluding that these devices permit to reduce remarkably stresses in the porcelain insulators. Alessandri et al. [6,7] also investigated the effectiveness of a base isolation system including adequately designed WRIs in reducing the seismic demand of a high voltage ceramic circuit breaker.

In the research literature there are no applications of WRIs in the seismic isolation of structures, such as new or existing buildings or bridges. Indeed, although WRIs are generally stiffer in the vertical direction than in the other two principal horizontal directions [2], namely, Roll and Shear directions, the value of the vertical load which can be supported by these metal devices is not high enough to allow their use for the seismic protection of structures. However, a shaking table experimental campaign, performed at the Department of Structures for Engineering and Architecture of the University of Napoli Federico II (Italy) on a scaled structure mock-up, seismically isolated using four curved surface sliders and four WRIs, have shown that the latter can be strongly useful when the complete recentering of the base-isolated structure is required and when the displacements of the base isolation system have to be reduced [8].

In order to allow the use of these metal devices with other different types of seismic isolators, such as sliding or elastomeric bearings, for the seismic protection of lightweight structures, an accurate characterization of their mechanical properties is required. The experimental studies described in [2,6,7] do not provide enough information to investigate the use of WRIs in a base isolation system of a seismically base-isolated structure. Indeed, their dynamic behavior in Roll and Shear directions and the influence of the vertical load have been studied only in the small displacements range.

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To this end, an extensive series of dynamic tests was conducted at the Laboratory of the Department of Industrial Engineering of the University of Napoli Federico II (Italy) on four different WRIs, by imposing cyclic sinusoidal displacements having different amplitudes and frequencies, under different values of the vertical load. More specifically, this experimental program was aimed at studying the influence of the displacement amplitude, frequency, vertical load, device geometrical characteristics and wire rope diameter on the dynamic behavior of the selected WRIs in the two principal horizontal directions. In addition, static tests were also carried out to evaluate the static to dynamic effective stiffness ratios for different values of displacement and applied vertical load.

In order to predict the horizontal dynamic behavior of WRIs, a mathematical model is required. The most widely used analytical model, able to describe their nonlinear hysteretic behavior, is the differential equation Bouc-Wen Model (BWM) [2]. In the present work, a one-dimensional (1d) Nonlinear Exponential Model (NEM) is proposed to simulate the dynamic response of these metal devices within a relatively large displacements range. The proposed model allows one to simulate the increase of the tangent stiffness observed at larger displacements, by avoiding the numerical solution of the first order ordinary nonlinear differential equation required in the BWM, and to reduce the number of model parameters to be identified. The mathematical model has been validated by means of comparisons between the experimental hysteresis loops obtained during the cyclic tests and those predicted analytically.

2. Description of tested devices

The selected WRIs, manufactured by Powerflex S.r.l. (Limatola, Italy), are made of a wire rope wound in the form of a helix and two slotted metal retainer bars in which the cable is embedded, as shown in Fig. 1(a). The cross section of the wire rope, which is constructed by winding a number of strands around an inner core, is shown in Fig. 1(b). Each strand has an axial member around which the individual metal wires are wrapped. The rope of the tested devices is made of six strands, each having 25 steel wires, plus a central one with 49 wires. The material of the wires is American Iron and Steel Institute (AISI) Stainless Steel Type 316 whereas the material of the two metal bars is aluminum alloy.

In order to study the influence of the height to width ratio, h/v, of the loop and the wire rope diameter, d_r, on the dynamic behavior of WRIs in the two principal horizontal directions, namely, Roll and Shear directions, four devices having 8 loops have been selected for experimental tests. Their geometrical characteristics are presented in Table 1 with reference to Fig. 2.

3. Experimental study

The experimental campaign presented in this section was aimed at studying the influence of the displacement amplitude, frequency, vertical load, device geometrical characteristics and wire rope diameter on the dynamic behavior of WRIs in Roll and Shear directions. Since in a base-isolated structure the maximum vertical displacement of the base isolation system is considerably smaller than the horizontal one [8], in this work, only the dynamic behavior in the horizontal directions has been studied. Static tests have been also carried out to better investigate the static horizontal response of these devices in three displacements ranges, under different values of applied vertical load. The experimental set-up and the dynamic and static tests are described in the following.

3.1. Experimental set-up

The experimental investigation of the dynamic and static responses of WRIs in the two principal horizontal directions has been performed by adopting the testing machine (TM) available at the Laboratory of the Department of Industrial Engineering of the University of Napoli Federico II (Italy) [9]. As shown in Fig. 3, the TM consists of two hydraulic actuators for loading in both horizontal and vertical directions, thus allowing one to impose horizontal displacement or load histories to the tested device with a constant vertical compression. Four guiding rollers, two on each side of the horizontal lower frame, prevent lateral movement of the TM basement. This equipment can be used as a 1d shaking table machine [10,11]. The maximum vertical force, exerted by

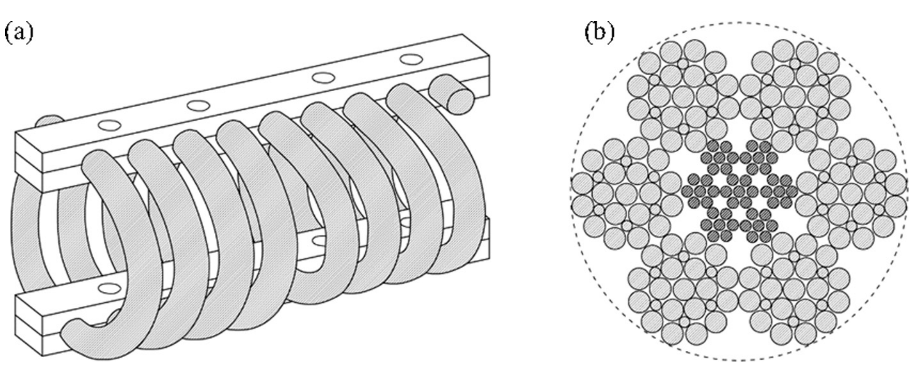

Fig. 1. (a) Wire rope isolator; and (b) wire rope cross section.

Table 1
Geometrical characteristics of tested WRIs.

WRI	l [mm]	h [mm]	v [mm]	h/v	d_r [mm]
PWHS 16010	267	100	110	0.90	16
PWHS 16040	267	125	150	0.83	16
PWHS 16040 S	267	125	150	0.83	19
PWHS 16060	267	145	185	0.78	16