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Non-destructive testing on aramid fibres for the long-term assessment of interventions on heritage structures.

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Abstract. High strength fibre reinforced polymers (FRPs) are composite materials made of fibres such as carbon, aramid and/or glass, and a resin matrix. FRPs are commonly used for structural repair and strengthening interventions and exhibit high potential for applications to existing constructions, including heritage buildings. In regard to aramid fibres, uncertainties about the long-term behaviour of these materials have often made the designers reluctant to use them in structural engineering. The present study describes simple and non-destructive non-linearity tests for assessing damage or degradation of structural properties in Kevlar fibres. This was obtained by using high precision measurements to detect small deviations in the dynamic response measured on fibres and ropes. The change in dynamic properties was then related to a damage produced by exposure of the sample to UV rays for a defined time period, which simulated long-term sun exposure. In order to investigate the sensitivity of such an approach to damage detection, non-linearity characterisation tests were conducted on aramid fibres in both damaged and undamaged states. With the purpose of carrying out dynamic tests on small fibre specimens, a dedicated instrumentation was designed and built in cooperation with the Metrology Laboratory of the Department of Electronics at the Politecnico di Torino.

1. Introduction

Aramid, carbon and glass fibres are typically exploited in composite materials and have been taken into account for use in structures for more than 20 years. The fibres are the primary load-carrying elements and provide the composites with their unique structural properties.

They possess a combination of high strength, high stiffness and good resistance to creep and corrosion, non-magnetic properties and they are resistant to various types of chemicals. For these reasons, they are perfect for the application in harsh environment [1, 2]. Depending on the type of application, the fibres can be oriented in different direction in order to enhance the mechanical properties of the composite in desired direction.

Areas that exploit these novel materials are, for example, external and internal pre-stressing devices, strengthening of structures through composite plates, composite bars as reinforcement, composites in the marine and railway industries and in ground engineering. The different uses of novel materials in civil engineering can be summarized in applications for new construction, repair and rehabilitation. It has been demonstrated that structures such as a bridges and columns built according to this technique show exceptional durability, and effective resistance to effects of environmental exposure. Several companies around the world begin to wrap damaged bridge piers to prevent collapse



and steel-reinforced columns to improve the structural integrity and to prevent buckling of the reinforcement.

Interesting applications of FRP materials are typically found in the cultural heritage field, where invasiveness of interventions is a major issue. Carbon fibre reinforced polymers (FRPs) are commonly employed for the strengthening and seismic retrofitting of vaults and other masonry elements of heritage buildings (Figure 1). In any case, experimental studies are still required to better understand the durability and compatibility of interventions in polymeric materials and, in general, in other non-traditional materials. For instance, uncertainties about the long term behaviour of aramid fibres made often designers reluctant to their use in the structural engineering fields.



Figure 1. (a) The masonry vault and reinforcement arches dated 1600 during surface preparation for CFRP application. (b) Smart CFRP sheet placed on vault [3].

The aim of this study is to show how simple and non-destructive non-linearity tests can be used for assessing the degradation of structural characteristics in aramid fibres. The idea is to detect weak non-linearities [4, 5, 6] in the dynamic response measured on fibres and ropes and to use this non-linearity level as an indicator of the aramid element's residual life. A degradation of the material properties was produced by exposing samples to UV rays for a defined time period, so as to simulate long-term sun exposure.

2. Testing equipment

In order to analyse the dynamic behaviour and to detect the presence of non-linearities in two samples of Kevlar®, in the case of pristine and damaged conditions, respectively, a dedicated testing device was designed and built ad hoc in the Metrology Laboratory of the Department of Electronics of the Politecnico di Torino.

The testing machine frame (Figure 2.a) is composed of a rectangular crossbeam ($L=45$ cm, cross section: 4×4 cm) made of aluminium, transversely bounded at two cylindrical aluminium holed columns ($h=95.4$ cm; diameter: 5 cm, thickness: 0.5 cm) on a massive square basement (60×60 cm) made of marble with a thickness of 14.5 cm. An isolation steel table supports the marble mass, this allowing to neutralize most of environment vibrations. The materials used for the testing system were selected in order to minimise the effect of the temperature excursion in the laboratory.

The specimen, consisting of parallel fibres, were mounted vertically, with the top fixed at the horizontal crossbeam and at an aluminium block at the lower part; a special device was inserted at the bottom in order to measure the specimen displacement during the test (Figure 2.b).

To evaluate the displacement of the fibre, an optical measurement system composed by an 8-millimeter sphere made of optical glass was used. It was used to focus the beam of light inside the photodiode. The photodiode was wired to an electronic circuit, capable of turning the optical signal into an electric one.



Figure 2. (a) The testing setup. (b) Micrometer slides, magnet for forced oscillation testing and hung mass. (c) He-Ne laser beam generator, attenuator and mirrors. (d) Schematic representation.

Therefore, a laser generator, an attenuator, 3 mirrors, a photodiode and a micrometre slide compose the measurement equipment.

A helium-neon generator was used for the experiment (Figure 2.c) in order to produce the laser beam. The device is able to emit a coherent, monochromatic and concentrated light beam in a highly collimated beam straight, through the process of stimulated emission. The laser generator is mounted on a suitable support, so that the laser beam was emitted in the horizontal direction with respect to the anti-vibration table.

An attenuator is an electronic device that reduces the power of a signal without appreciably distorting its waveform. The attenuator was used to prevent saturation of the photodiode, attenuating the beam light (Figure 2.c).

Metal mirrors were used to adjust the direction of the laser beam. They were mounted on supports in order to be adjusted for different inclinations. The combined movement of rotation about the horizontal and vertical axes of the two mirrors allows to determine completely the direction of the light beam (Figure 2.c).

A photodiode, which converts an optical signal to an electric signal, was mounted on three precision micrometre slides. Two of these were assembled together in reference to the X-direction (parallel axis to the plane formed by the optical bench and orthogonal to the laser beam) and Z-direction (orthogonal axis to the plane formed by the optical bench and orthogonal to the laser beam direction). The third slide is positioned in a parallel direction to the bench and the laser beam (Figure 2.b).

In Figure 2.b it is also possible to notice the hung mass of 1.375 kg which was used to form a 1-DoF system with the specimen acting as spring. A copper wire coil was placed inside a magnet and aligned so that an electromagnetic force in the vertical direction could be produced and applied to the hung mass and, consequently, to the fibres (Figure 2.b).

2.1. Principle of operation

The principle of operation of the instrumental apparatus used in the tests (Figure 3) can be summarized in the following stages. The light source produced by the laser generator was forced to follow a predetermined path by means of a prism and two lenses. These lenses, if properly set, deflected the laser beam causing it to converge towards the instrument test, where the sample was allocated. In order to allow the photodiode to read the optical signal and, consequently, the possible displacement of the fiber, a glass sphere (connected to the hung mass) with a diameter of 8 mm was used, which, working as a convex lens, focuses the beam to a very precise point of the marker located inside the photodiode (Figure 2.b). The marker was divided into four sectors, generally square. The sensor read the movement of the glass sphere and indirectly the elongation of the fiber, in relation to the quadrant where the laser beam was focused. Therefore, it was important to make a correct positioning of the

photodiode using the micrometer slides. Indeed, for the system in a quiescent state, the read signal was set equal to zero. An electronic circuit was used to link the photodiode to an oscilloscope. An acquisition card and a Lab View application were used to record the collected data on csv files.

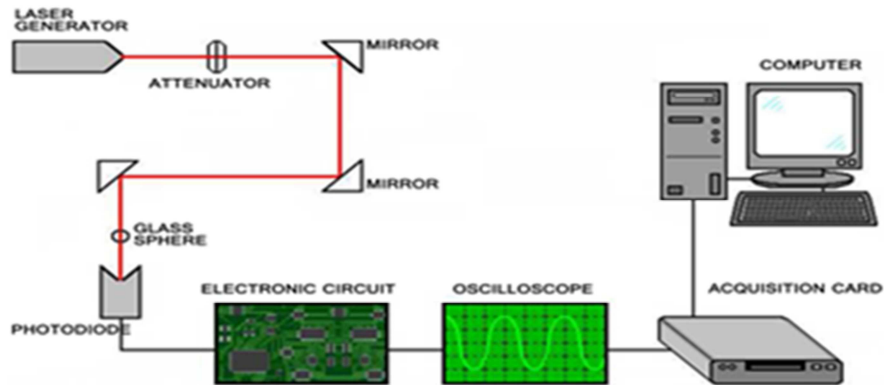


Figure 3. Principle of operation - schematic representation.

3. Samples and UV damage

The samples used for the experimental tests were provided by SIGIT s.n.c [7], which trades high-tech materials. In this specific case, the material under investigation is a para-aramid yarn of Kevlar-29 (100% purity), made with DuPont production, length 0.67 m. The bundle of fibres in Kevlar-29, used as a sample, has counted equal to 2500 dTex; this means that 10000 m of yarn (in length) weigh 2500 g. Thanks to these data, it was possible to evaluate with good accuracy the value of the cross section area of the sample that is equal to $1.77 \cdot 10^{-7} \text{ m}^2$; the diameter of the single fibre is $15 \mu\text{m}$ and thereby, the yarn is composed by about 1000 fibres. To obtain the elastic modulus, tensile tests were carried out on specimens with a length of 0.067 m, and the result is 84.5 GPa on single fibre.

The type of process chosen to cause damage has been the prolonged exposure to ultraviolet rays. Many natural and synthetic polymers are attacked by UV rays. This problem is known as UV degradation, and is especially common in products constantly exposed to sunlight. In this work, this method of damage was chosen because a continuous exposure results to be more harmful than intermittent one, since the danger depends on the intensity and the degree of exposure. The polymers possessing UV-absorbing groups such as aromatic rings can be subjected to the effect of ultraviolet radiation. In particular, aramid fibres such as Kevlar, are very sensitive to UV light and must be often protected from the deleterious effects that the sunlight might have.

In order to perform such a test, a UV lamp for industrial applications, an OSRAM Ultra Vitalux, was chosen. The composition of the radiation of this light is similar to the mixture of radiation of natural sunlight, in the alpine environment. It emits a mixed light, generated from a tungsten filament in conditions of high pressure; furthermore, the special mushroom shape, with internal reflector, ensures the passage of a high fraction of UVA and UVB, while it tends to absorb more harmful UVC radiation.

Regarding the damage test, the lamp was mounted on a support constructed ad hoc in the Metrology Laboratory of Politecnico di Torino with recycled materials, so that the distance between the edge of the lamp bulb and the sample was about 0.50 m. A cylinder made of sheet metal with a diameter of 0.13 m was used for conveying light toward the sample (which must be damaged) and there was also taken care to leave an open space below the cylinder, to ensure that natural recirculation of air during the test.

The sample was then subjected to a cycle of continuous exposure to 772 hours, turning the fibres once a week, in order to obtain a uniform damage as possible over the entire surface of the material.

4. Experimental tests and results

Once all possible uncertainties on the measurements of the testing machine were analysed and handled with, real data begun to be acquired. Through experimental measurements, it is possible to characterise the material under investigation and identify the behaviour from the dynamic point of view. It should be underlined that, in order to compare the results obtained from the pristine and damaged fibres, the experimental tests were performed at a constant temperature (21°C).

The dynamic response of a system can be analysed in different ways. Free-decay and forced oscillations at resonance tests were carried out on both pristine and damaged specimens. The mass of 1.375 kg was sufficient to let the fibers tight and it induced a tension that corresponded roughly to a 10% of the tensile strength for the Kevlar®-29 samples.

4.1. Free-decay testing

In order to characterise the dynamic behaviour of the fibres, free-decay tests were performed. The tests allowed for the identification of natural frequencies and damping ratios of both specimens. The system identification was achieved with time domain fitting techniques applied to the Hilbert transform envelopes of the acquired signals (Figures 4 and Figure 5). Results were also validated by using standard ERA techniques [8].

The application of curve fitting techniques over free-decay signals sampled at 2500 Hz gave for the Kevlar-29 pristine samples, a resonance frequency of (20.30 ± 0.03) Hz and an experimental damping ratio of $(0.7 \pm 0.1) \%$; whilst for the Kevlar-29 damaged samples, a value for natural frequency of (19.80 ± 0.02) Hz and experimental damping ratio equal to $(0.6 \pm 0.1) \%$ were evaluated. The spread of the results was computed using 7 free-decay measurements for both samples. The high sensitivity of the measurement device allows to quantify low damping ratio and frequencies with a high level of accuracy. These damping ratios can be directly linked to the intrinsic material dissipation factor, because all other dissipation phenomena can be actually neglected. The mean value of the natural frequency was used to estimate the elastic dynamic modulus of the fibres.

The results show that there is a relevant variation of the natural frequency correlated to the damage suffered by the continuous UV exposure for 772 hours the Kevlar-29 sample.

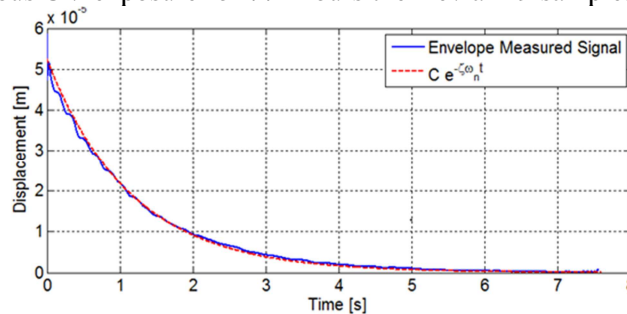


Figure 4. Kevlar-29 pristine sample: fitting of the envelope of the acquired signal.

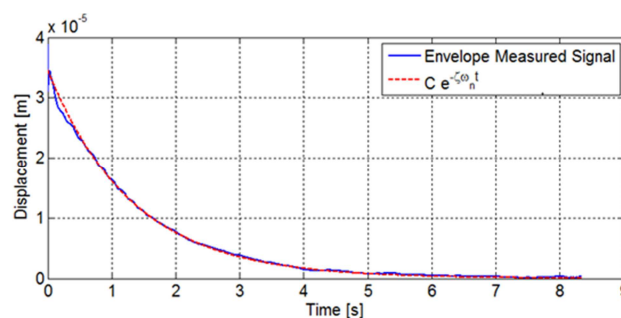


Figure 5. Kevlar-29 damaged sample: fitting of the envelope of the acquired signal.

4.2. Forced oscillations

In order to highlight possible non-linearities, campaign with harmonic forced excitation tests was set up. The frequency range investigated was of ± 0.200 Hz with respect to the resonance frequency of the system, with a step excitation frequency chosen equal to 0.010 Hz while keeping the force constant. Then the test was repeated for different level of force, the amplitude being varied by adjusting the voltage applied through a function generator in steps from 3 V to 10 V, corresponding to forces induced by the electromagnetic field that were in the approximate range of 10-30 mN (see Figure 2.b and 2.d). The value of the amplitude of the static force at resonance was estimated at approximately 0.9 N at the lowest level applied, and 3.1 N at the highest.

Once the input voltage interval has been defined, changing the frequency of the driving force (via the function generator) it is possible to record the values of the output voltage, from which the displacement can be determined by using a conversion factor established during the photodiode calibration. The results are reported in Figure 6 and Figure 7.

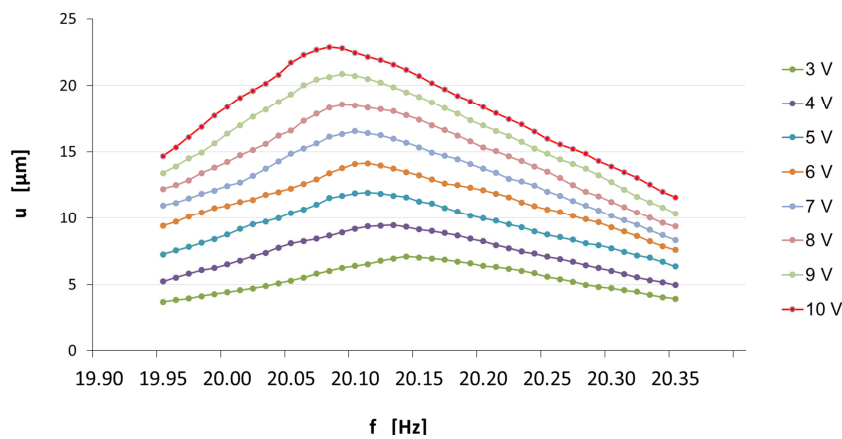


Figure 6. Response spectra for increasing values of the input force – pristine sample.

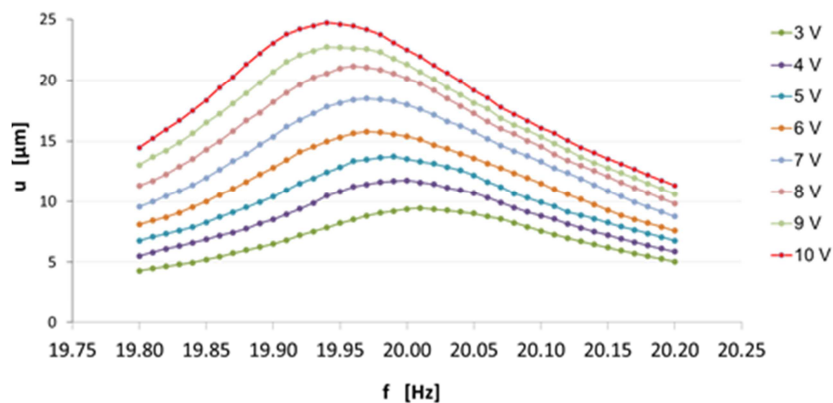


Figure 7. Response spectra for increasing values of the input force – damaged sample

4.2.1. *Non-linear identification of the backbone curve.* To define the dynamics of a system characterised by cubic non-linearity excited by a harmonic force, the following expression found in literature is exploited. The distortion in frequency f was quantified as:

$$f = f_n \left[1 + \frac{3\chi}{8k} a^2 \right] \tag{1}$$

where a is the amplitude of the response, k is the linear stiffness, f_n is the natural frequency and χ is the cubic stiffness coefficient. Equation (1) is related to the following Duffing oscillator equation:

$$m\ddot{x} + c\dot{x} + kx + \chi x^3 = F \tag{2}$$

where F is the external force, m the mass of the system and c the linear viscous damping.

In order to try to identify the non-linearity, the Krylov-Bogoliubov method was used to determine the variation of the first non-linear resonance frequency of a Duffing oscillator [6, 9].

Equation (1) was used to identify the so-called back-bone non-linear curve of the response, as it is highlighted by a red line in Figure 8 and Figure 9.

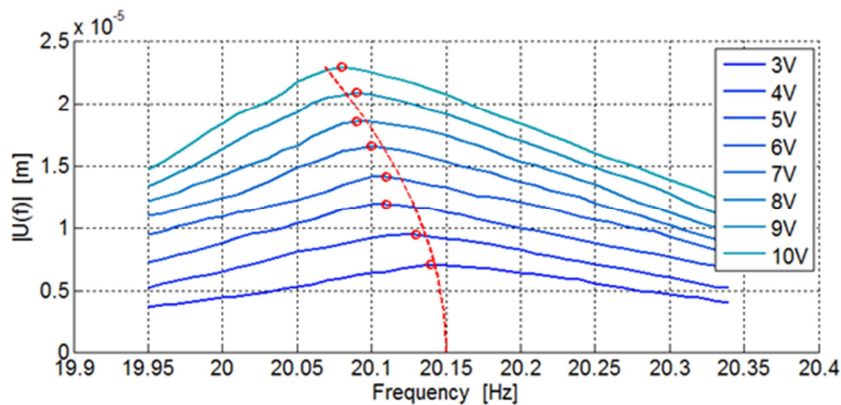


Figure 8. Back-bone nonlinear curve identification - undamaged Kevlar-29 sample.

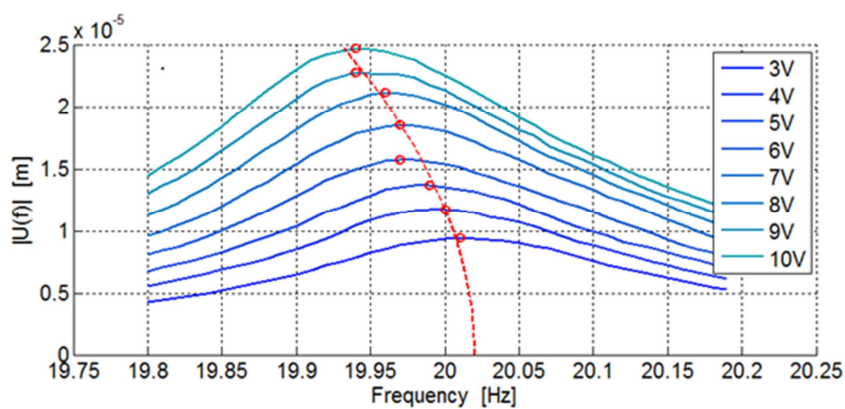


Figure 9. Back-bone nonlinear curve identification - damaged Kevlar-29 sample.

For the first Kevlar-29 (not damaged sample) the non-linear stiffness χ was identified at $-3.23 \cdot 10^{11}$ N/m³, whilst for the second Kevlar-29 sample (after damage) it was ca $-3.04 \cdot 10^{11}$ N/m³.

From Figures 8 and 9, where the backbone non-linear curves were represented, no significant differences can be appreciated between the pristine and damaged samples, as regards the inclination of the back-bone curve and the value of the index of non-linearity.

Anyway, this approach confirmed the high-sensitivity of the testing device also to low-levels of non-linearity.

Conclusions

The aim of this research has been to perform simple non-destructive non-linearity tests for damage assessment of aramid fibres and elements. The underlying idea was to use the existence of weak non-linearities, which can be detected in the forced dynamic response of the specimen, as indicators for safety and lifecycle assessment. To reach this goal, two samples of the same innovative material were tested: one pristine bundle of fibres in Kevlar-29 and another bundle which had been damaged.

Comparing the results obtained for the two samples, no significant differences emerged with respect to the non-linearity index under investigation ($-3.23 \cdot 10^{11}$ N/m³ for the pristine sample as compared to $-3.04 \cdot 10^{11}$ N/m³ for the damaged sample). Instead a weak variation was evident in the natural frequency value related to the free-decay test responses (20.30 ± 0.03) Hz in the pristine sample vs. (19.80 ± 0.02) Hz, in the UV damaged sample).

The experimental results presented in this paper will be of use in evaluating the actual feasibility of Kevlar retrofitting interventions on existing structures. In particular, the demonstrated sensitivity to UV rays, in terms of decreased stiffness and potential relaxation, may be a discriminating factor when choosing the type of aramid material to be employed for the confinement interventions on concrete or masonry columns, or vaults in historic buildings.

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