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Characterisation of a wood pole tester

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***Abstract* – Wood is widely employed to support aerial cables for electrical energy and telecommunication networks. Being a natural material, it is subject to decay, which requires periodic structural inspections. This paper present the metrological analysis of a vibration-based pole testing system, taking into account different contributions to uncertainty as well as the effects of natural variability of wood properties. The study allows to evidence the main features and intrinsic limits of the test approach and shows how performance bounds have been evaluated.**

I. INTRODUCTION

Wooden poles play a significant, though largely unnoticed, role in our technological society. Wood is, possibly, the most widely employed material in the realization of aerial cable supports for electrical energy and telecommunication networks. In most countries, overhead lines in low- and medium-voltage power distribution networks rest on wooden pole structures. Likewise, in several places wired communication landlines are built with aerial cables on wooden poles.

In Italy alone such poles number a few million, whereas in the United States a quick count places the number at an astonishing 80 million units. Hence, many of the advanced facilities that are taken for granted in everyday life can be said to, literally, rest on wood.

Being a natural material, wood is subject to degradation that may result in impairments to its structural properties. Therefore, periodic inspection of structural integrity is required to prevent loss of service, as well as to ensure the safety of maintenance crews, actually climbing on poles, and of ordinary people nearby.

Traditionally, pole inspection is entrusted to a qualified technician, who relies on his experience to judge the soundness of the pole by assessing its vibrational behaviour and/or the sound it makes when hit by a hammer. A few suspect cases can be further analysed by instruments (such as a force-measuring drill) but, in most cases, subjective factors play a large part in the outcome of the inspection, which may happen to be biased as a consequence. Trials show that quality grading performances are variable, with some individuals achieving error rates no better than 30%.

Cinetix S.r.l., a company located in Padua, Italy, designs and manufactures a non-invasive test system, currently being sold worldwide, that aims at providing a more objective assessment of pole structural properties. In its present form the system, called *CXI-PT5500*, is a data acquisition and vibration analysis system, whose measurements are input to a finite-element mechanical model to obtain the estimate of a pole ultimate breaking strength (UBS). Objective assessment based on *CXI-PT5500* measurements typically yields a four-fold improvement over the worst-case error rate cited above, resulting in better planning of pole replacement and significant maintenance economies. Characterisation of *CXI-PT5500* performances by uncertainty and error rate analysis is required to allow better understanding of the measurement problem and how it is addressed by, which is a prerequisite to further development of the system.

The purpose of this paper is to present the metrological analysis of vibration-based pole testing, where different contributions to uncertainty are highlighted and the aspect of natural variability of wood properties is taken into account. As this aspect is much more significant than in the case of human-made artefacts, the study allows to evidence intrinsic limits of the test approach and shows how performance bounds have been evaluated.

II. OPERATING PRINCIPLES

The pole testing system analyses vibrational data, acquired by accelerometers, to determine characteristic vibration frequencies of a wooden pole. The measured frequencies are then matched with a structural model that allows the estimation of the modulus of elasticity E. Laboratory tests have shown good agreement between this value, measured under dynamic conditions, and measurements in a static test rig according to EN 14229 [1].

The estimate of pole UBS is then calculated from the expression that links the applied force to geometric parameters of the pole and to its maximum bending strength σ_{max}, assuming the following conditions:

1. the pole has a constant and uniform modulus of elasticity;
2. the relationship between E and σ_{max} can be expressed by a monotonic function:

$$\sigma_{max} = f(E) . \tag{1}$$

Assuming approximation of a wooden pole shape as a circular cross-section with a linear taper, the location of the maximum bending stress can be determined by applying the theory of linear elasticity. Although actual values depend on the taper of the pole, in practice variations are limited enough to allow the assumption of maximum stress at ground level. Then, the following first-order expression can be obtained:

$$Q_{\max} = \sigma_{\max} \frac{\pi d_g^3}{32} \cdot \frac{1}{L_a} \ , \qquad (2)$$

where d_g is the diameter of the pole at ground level and L_a is its height above ground. Therefore, UBS value $Q_{\max}$ can be obtained by combining measurements of simple pole dimensions with the indirect determination of $\sigma_{\max}$ through measurement of *E*.

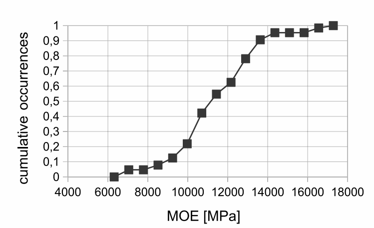
III. CALIBRATION

The determination of $f(E)$ is an essential part of the calibration process. Wood properties relevant to the test are in fact summarised into relationship (1) that also has to account for variability, caused by the environmental conditions the pole has been exposed to. It is important, therefore, to find a suitable mathematical expression to interpolate experimental calibration data.

A. Test data

Cumulative distributions reported in Fig. 1 refer to the measured values of the modulus of elasticity and modulus of rupture for a set of 64 fully-characterised wooden poles. As far as essence is concerned, the poles represent a homogeneous sample, all being made of pine wood coming form different North European areas. Conditions of use and degree of decay, however, may change.

a)



b)

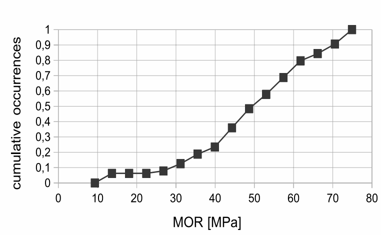


Fig. 1. Cumulative distributions of measured values:
a) modulus of elasticity (MOE); b) modulus of rupture (MOR)

After more or less prolonged service supporting telecom wired lines, these poles were taken to a laboratory and measurements of their dimensional parameters, moisture content and mechanical properties were carried out. The resulting data set provides the basis for the determination of a calibrated relationship between *E* and σ_{max}. A simple fit could be based on a linear regression over the whole set of 64 value pairs. The value of the correlation coefficient obtained in this case is less than 0.4, which may appear to indicate a bad fit but is actually related more to the variability of wood mechanical properties.

The residue of the linear fit is approximately within ±50% of the measured value. More importantly, larger residues occur near the ends of the measured range. In particular, lower values of σ_{max} are overestimated, which might cause misdetection of pole faults.

It should be noted that linear regression parameters are data set dependent. In trials on 6 different subsets, data for 8 poles at random were deleted from the original data set, regression slope variability being about ±10%. However, neither the correlation coefficient, nor the standard deviation of residues changed significantly as a consequence. It can therefore be assumed that a variation of this order of magnitude has little relevance, since variability in experimental data is larger.

In this respect, it has to be remarked that the coefficient of variation (COV, i.e., the ratio of standard deviation to mean value) for the calibration data set is larger than the typical values reported in ANSI O5.1-2008 [2]. The latter are provided as references for reliability-based design and refer to new poles, whereas the larger COV in test data reflects the wide range of service conditions the poles in the test set had been subjected to, resulting in variable degrees of decay for part of them.

B. Non-linear fitting

An alternative fit of experimental data has been experimented with, based on the use of sigmoidal functions. Results are shown in Fig. 2, where the fit of data is based on the functions:

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \qquad \text{or} \qquad l(x) = \frac{1}{1+e^{-x}} \ , \qquad (2)$$

that are, respectively, a suitably normalised Gaussian error function and a logistic function. These equations fit the data set well enough, as shown in Fig. 2. In fact, *erf*(*x*) consistently provides a better correlation coefficient than the linear fit.

Residues of sigmoidal fits were found to be larger than those of the linear fit. However, the use of a sigmoid has two main benefits:

- parameters can be initialised rather easily, given an assumed range of values;
- residues obtained by sigmoidal fits tend to be less correlated to values of σ_{max}.

a)

b)

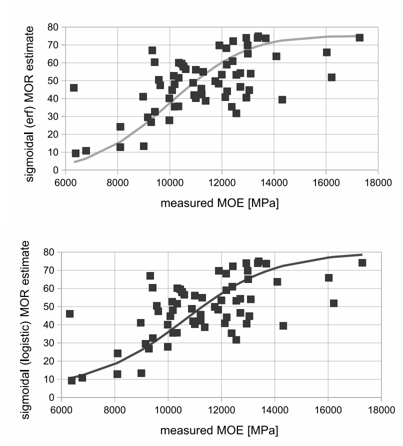


Fig. 2. Sigmoidal fit of σ_{max} for the 64-sample set: a) Gaussian error function; b) logistic function

Analysis of cumulative distributions of residues showed that the intervals from 5% to 95% of the occurrences cover the range from -20 to +20 MPa for the linear fit, and from -25 to +25 MPa for the two sigmoidal fits. Accordingly, standard uncertainty on the estimate of σ_{max} is taken to be 15 MPa since, for all fitting methods, those intervals are equivalent to less than four times the residue standard deviation.

This rather large value of standard uncertainty emphasises that relationship *f*(*E*), as derived from the data set, has to be regarded as representative of its average properties, particularly for such an assorted population and specific to the wood essence under investigation.

IV. UNCERTAINTY ANALYSIS

To fully characterise the pole testing system, analysis of uncertainty needs to consider three main contributions: geometric measurements, determination of the module of elasticity and the rather large uncertainty contributed by the definition of empirical relationship (1). From (2), applying the probability-based approach considered in [3], the standard uncertainty u_{Qmax} for the limiting load Q_{max} follows as:

$$u_{Q_{max}}^2 = u_{\sigma_{max}}^2\left[\frac{Q_{MAX}}{f(E)}\right]^2 + u_d^2\left[3\frac{Q_{MAX}}{d_g}\right]^2 + u_L^2\left[\frac{Q_{MAX}}{L_a}\right]^2, \qquad (3)$$

where $u_{\sigma max}$, u_d and u_L are the standard uncertainties in the determination of the maximum bending strength, the diameter and the length of the pole above ground level, respectively. Evaluation of uncertainty in geometric measurements is straightforward and relative values for u_d and u_L have been assessed to be between 2% and 5%, depending on field conditions. *E* is measured directly by the instrument [4] and its uncertainty is also comparatively limited.

A much larger relative contribution to standard uncertainty comes from the estimation of σ_{max} through (1). It is useful, as a preliminary step, to re-write (3) in the form:

$$u_{Q_{max}} = \frac{\pi d_g^3}{32}\cdot\frac{1}{L_a}\sqrt{u_{\sigma_{max}}^2 + f^2(E)\left[3\frac{u_d^2}{d_g^2}+\frac{u_L^2}{\left(L_a\right)^2}\right]} \cong \left(\frac{\pi d_g^3}{32}\cdot\frac{1}{L_a}\right)u_{\sigma_{max}} \qquad (4)$$

where the smaller contributions due to dimensional uncertainties are neglected in the approximation. The latter expression evidences a linear dependence on the geometric factor (between parentheses), which is confirmed in the plot of Fig. 3, where u_{Qmax} was calculated using (3).

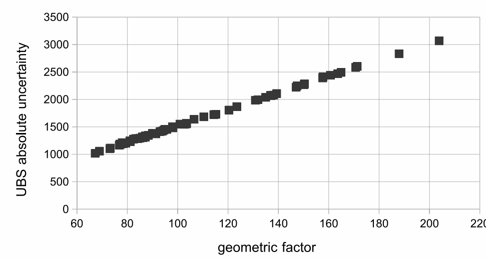


Fig. 3. Ultimate breaking strength absolute uncertainty versus geometric factor for the 64-sample set.

From a practical point of view, the approximate expression (4) is of particular interest, since it allows to readily assess the standard uncertainty in the determination of UBS for any *individual* pole under test. In fact, the geometric factor can be readily determined by field measurements of the pole and $u_{\sigma max}$ is known in advance as a result of the data fit carried out in the calibration procedure.

It should be remarked that, within the limits of lengths and tapers in common use, pole geometry can be considered independent of σ_{max}, as shown in Fig. 4. Although the plot may suggest grouping data, according to geometric factor, into two subsets (e.g., “slim” vs. “thick”), the range of measured values for the modulus of rupture remains approximately the same.

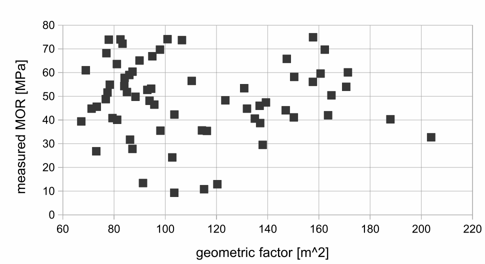


Fig. 4. Measured modulus of rupture versus geometric factor for the 64-sample set.

The analysis that follows will show how a test criterion that successfully supports pole acceptance trials can be developed with good results.

V. POLE TESTING

In-service testing of pole strength is, in first place, a pass/fail experiment to decide whether a wooden pole is still fit for service, or a replacement is needed. For this purpose, a threshold needs to be set while accounting for uncertainty of the measuring device. Let Q_{lim} be the acceptable strength limit. The acceptance threshold Q_{th} is then set as:

$$Q_{th} = Q_{\lim} - u_{Q_{\max}} , \quad (5)$$

that means measurement uncertainty is taken into account by lowering the tolerance limit [5].

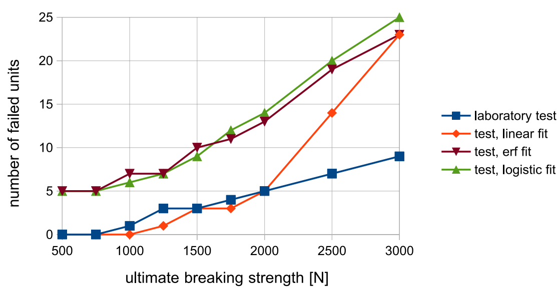


Fig. 5. Number of failed units within the 64-sample set.

Results reported in Fig. 5 show the number of poles that fail the test, at a given UBS value, using different calibration functions $f(E)$. Results of laboratory tests are presented in the same plot as a reference. It can be seen that the two non-linear functions yield very similar results, with a substantial conservative margin over laboratory tests.

Table 1. Pole test false positives.

threshold	linear fit	erf fit	logistic fit
1000	0	6	5
1250	0	4	4
1500	1	7	6
1750	1	7	8
2000	2	8	9
2500	7	12	13
3000	16	16	18

Although linear fit results are closer to laboratory test outcomes at low values of UBS, they result in a number of false negatives, which may cause potential safety hazards. This is evidenced, in Fig. 5, by the fact that the "linear fit" curve is lower than the "laboratory test" one. Non-linear calibration curves produce no false negatives, up to the highest UBS threshold of 3000 N.

On the other hand, a test system using the non-linear function $f(E)$ does yield a number of false positives, that is, still healthy poles for which replacement is suggested. While this causes no hazard as far as safety is concerned, it represents an additional cost, that utilities also wish to minimise.

False positive results are summarised in Table 1. Tuning of threshold (5) may reduce these numbers, in particular the margin represented by u_{Qmax} can be reduced using a factor smaller than 1. It has to be remarked that it is extremely hard to reliably determine an *a-priori* false-positive probability, since values presented in this work are obtained from what, for statistical purposes, is still a comparatively limited data set.

VI. FINAL REMARKS

Calibration of a test system for wooden poles, following common industrial practice, is an extremely challenging undertaking. Intrinsic variability of natural materials like wood, as opposed to industrial products, is much higher. As a consequence, reliability-based analysis requires the introduction of significant safety coefficients. For the same reason, it is much harder to predict test risks from a commercial viewpoint.

Results presented in this paper show how variability can be handled to satisfactorily predict uncertainty. Furthermore, the choice of a suitable calibration procedure ensures that test results support safety first, while keeping commercial risk at a reasonable level.

In this regard, improvements are more likely to come for the integrated use of different test techniques. Planned development of the test system includes the integration of new analysis techniques, for enhanced discrimination of structural impairments.

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