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Probabilistic models for mechanical properties of prestressing strands

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HIGHLIGHTS

- ▶ The study shows the low variability of the mechanical properties of strands.
- ▶ During the period analysed (2001–2009) the properties did not show any trend.
- ▶ Generally, the results obtained agree with the results reported in PMC.
- ▶ However, some of the proposed models in the PMC should be updated.

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ABSTRACT

This study focus on the probabilistic modelling of mechanical properties of prestressing strands based on data collected from tensile tests carried out in *Laboratório Nacional de Engenharia Civil* (LNEC), Portugal, for certification purposes, and covers a period of about 9 years of production. The strands studied were produced by six manufacturers from four countries, namely Portugal, Spain, Italy and Thailand. Variability of the most important mechanical properties is examined and the results are compared with the recommendations of the *Probabilistic Model Code*, as well as the Eurocodes and earlier studies. The obtained results show a very low variability which, of course, benefits structural safety. Based on those results, probabilistic models for the most important mechanical properties of prestressing strands are proposed.

1. Introduction

The properties of prestressing strands have a considerable influence on the safety of prestressed structures, in particular bridges, as well as on the total construction cost. For this reason, it is fundamental to define adequately the mechanical properties of these elements. In this study, a statistical analysis of three families of strands with nominal diameters of 13.0, 15.2 and 15.7 mm (cross-section areas of 100, 140 and 150 mm^2, respectively) is presented. All strands have nominal tensile strength of 1860 MPa (Y1860 grade) and are all composed by seven wires. The analysed strands correspond to the most widely used world wide in the last decades.

Samples were collected from tensile tests performed between 2001 and 2009 in *Laboratório Nacional de Engenharia Civil* (LNEC), Portugal. During this period, over 500 tensile tests were carried out for the three families mentioned above. However, several of these tests refer to strands produced from the same heat (same casting). As it is known, the variability within a single heat is lower than the variability between different heats. Thus, for the purpose of statistical analysis, only one test from each heat was selected (at random), which reduced the sample to 131 tests.

Differently to what was done in a previous study [1], where stresses were computed dividing the forces measured in those tests by the actual strands cross-section areas, in the present study all the stresses were computed using nominal cross-section areas. This is common practice [2,4].

For each of the three families of strands, the studied properties were: tensile strength or maximum stress (f_p), 0.1% proof stress ($f_{p0.1}$), total elongation at maximum force (ε_u) and modulus of elasticity (E_p). It was found out that the difference in the mean of those properties between families was of the same order of magnitude as the standard deviations, which allowed us to consider the three families of strands as belonging to the same population. The three families were thus merged into a single sample.

The tested strands came from six manufacturers of different countries, including Portugal, Spain, Italy and Thailand. However,

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as it will be seen, the variability of the studied properties is very small, not justifying thus a separated analysis by manufacturer.

Fig. 1 shows a typical stress–strain diagram for a prestressing strand, with the corresponding mechanical properties indicated. The characteristic value of those properties (which are random variables), usually the 0.05-quantile, is denoted adding the letter k in lower script. For example, the characteristic value of the variable $f_{p0.1}$ will be denoted by $f_{p0.1k}$. As shown in Fig. 1, prestressing strands do not exhibit a distinct yield point, which is typical of high strength steels, presenting however a slight inflection in the beginning of the hardening zone.

As stated above, the studied strands are all of the Y1860 grade, which has been the most commonly used in Portugal and in other countries. The value 1860 is termed *nominal tensile strength*, expressed in MPa, and corresponds to the characteristic value of the tensile strength f_p, that is, f_{pk} = 1860 MPa [2].

The main purpose of this study is to analyse the variability of the mentioned mechanical properties of prestressing strands and compare it with the corresponding recommendations of the *Probabilistic Model Code* [5] and other sources. Based on this comparison, probabilistic models for the mechanical studied properties are proposed.

2. Critical review of the *Probabilistic Model Code* recommendations

Table 1 shows the recommendations of the *Probabilistic Model Code* (PMC) [5] concerning the tensile strength f_p, modulus of elasticity E_p and total elongation at maximum force ε_u of prestressing steels. As it can be observed, PMC presents two expressions for the mean of f_p, one of which assumes constant coefficient of variation and the other constant standard deviation. PMC gives no indication about which one should be used.

Regarding the 0.1% proof stress, PMC recommends for strands the model: $f_{p0.1} = 0.85 f_p$, which assumes a perfect correlation between f_p and $f_{p0.1}$. As it will be seen, this model deserves some reservations, and an alternative model is proposed in this study.

3. Statistical analysis of the available sample

This section presents the results of the statistical analysis performed and produces some comments on its relevance for the structural safety. It must be emphasised that the stresses were computed for all cases dividing the forces obtained from the tests by the nominal cross-section area of the strands, as it is usual [2]. In this way, the variability of the computed stresses (f_p and $f_{p0.1}$) already includes the variability of the cross-section area. Thus, in the model $F_p = f_{p0.1} \cdot A_p$, which gives the force in a cable, the area of the cable A_p must be modelled as deterministic. Nevertheless, the variability of the cross-section area is also analysed.

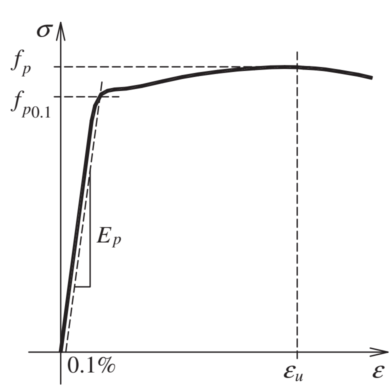

Fig. 1. Typical stress–strain diagram for a prestressing strand.

Table 1
Prestressing steels. Recommendations of the *Probabilistic Model Code* [5].

Variable		Mean	Std. dev.	V[a]	Distribution
f_P		1.04 f_{pk} or	–	0.025	Normal
		f_{pk} + 66 MPa	40 MPa	–	
E_P	Wires	200 GPa	–		
	Strands	195 GPa	–	0.02	Normal
	Bars	200 GPa	–		
ε_u		0.05	0.0035	–	Normal

[a] Coefficient of variation.

As mentioned earlier the three samples of strands (diameters of 13, 15.2 and 15.7 mm) were merged into a single sample. For a better appreciation of this aspect, Table 2 presents statistical summaries, separated for each family. As it can be seen, for all properties the difference in the means between families is of the same order of magnitude, or even lesser, as the standard deviation within each family. Moreover, the standard deviation, maximum and minimum values observed within each family are also very close across families. Therefore, there is no need to develop separated probabilistic models for each diameter. Merging the three samples into a single sample, the results become independent of the diameter.

3.1. Tensile strength

Fig. 2 shows the histogram of the tensile strength f_p of the tests available (131 tests). As it can be seen, the normal model fits well the histogram, which agrees with the PMC recommendations [5] and the prEN 10138-1 [2]. The coefficient of variation obtained is very low, V = 0.018.

According to the parameters obtained (μ = 1933 MPa, σ = 35 MPa), the characteristic value of f_p can be estimated as f_{pk} = 1933 – 1.645 × 35 = 1875 MPa, which satisfies the specified value for the Y1860 grade. The estimate of f_{pk} using directly the sample available (i.e., empirical distribution) is 1881 MPa.

These results agree with the results reported by other authors, namely Casas and Sobrino [6], Nowak and Szerszen [7], and Wisniewski et al. [8]. The value of 40 MPa for the standard deviation, as suggested by PMC, seems a reasonable assumption. So, for modelling the tensile strength the following model can be used:

$$f_p \sim N(\mu, \sigma); \quad \mu = f_{pk} + 1.645 \times 40 \text{ (MPa)}; \quad \sigma = 40 \text{ MPa} \tag{1}$$

Fig. 2b shows the values of the tensile strength f_p by production year, indicating that there is no trend during the observed period (2001–2009). This Figure also suggests that the sample is free of outliers.

3.2. The 0.1% proof stress

From the structural safety point of view, the 0.1% proof stress $f_{p0.1}$ is more decisive than the tensile strength, because this one is only reached for large strains, rarely observed in real structures, even for ultimate limit states.

Fig. 3 shows the histogram for the 0.1% proof stress and its temporal variation. As it can be seen, the 0.1% proof stress has greater variability ($\sigma_{fp0.1}$ = 51 MPa) than the tensile strength (σ_{fp} = 35 MPa), which agrees with results reported in earlier studies [6,8,9]. In fact the 0.1% proof stress is more sensitive than the tensile strength, because it depends on the measured modulus of elasticity and the curvature of the stress–strain diagram where the yielding starts. This finding raises a comment on the model $f_{p0.1} = 0.85 f_p$ proposed by PMC. According to this model the standard deviation of the 0.1%