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Statistical analysis of the material properties of selected structural carbon steels

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ABSTRACT

Modern design procedures for steel structures increasingly employ more realistic representations of the stress–strain behaviour of steel rather than a simple ideal elastic–plastic. In particular, for buckling failure modes in the plastic range, stresses in excess of the yield stress are always involved, together with a finite post-yield stiffness. Moreover, the 'plastic plateau' in buckling curves for stocky structural members cannot be predicted computationally without a significant strain hardening representation. If a good match is to be sought between experiments and computational predictions in the elastic–plastic zone, strain hardening must be included. Most studies have either used individual laboratory measured stress–strain curves or educated guesswork to achieve such a match, but it is not at all clear that such calculations can reliably be used for safe design since the same hardening properties may not exist in the next constructed structure, or even within a different batch of the same steel grade.

A statistical exploration is presented here to assess the reliable magnitudes of post-yield properties in common structural grade steels. For simplicity, only two critically important parameters are sought: the length of the yield plateau and the initial strain hardening tangent modulus. These two are selected because they both affect the elastic–plastic buckling of stockier structural elements. The statistical analyses exploit proprietary data acquired over many years of third-party auditing at the Karlsruhe Institute of Technology to explore possible regressed relationships between the post-yield properties. Safe lower bounds for the selected properties are determined.

1. Introduction

Early design concepts for structural members treated the behaviour as linear-elastic and limited the maximum stress to an 'allowable stress' related to a yield stress. Since an axially compressed stocky column is a structural form in which the mean axial stress can clearly exceed the yield stress before failure, early treatments of inelastic buckling such as those of Engesser [1,2] and Considère [3] used a fully nonlinear stress–strain curve. Their work was later extended into extensive buckling strength predictions for simple columns by Chwalla [4]. But in the same period, Jezek [5] was able to produce predictions for the strength of members under both axial load and bending provided the stress–strain curve was treated as ideally elastic–plastic. This difference indicates the simplicity that was then needed to address more complicated situations. With the development of the plastic theory of structural collapse [6,7], coupled with application to mild steel structures whose stress–strain relationship possesses a distinct yield plateau, it was highly desirable to continue with this ideal elastic–plastic model.

From that point onwards, the stress–strain relation for most metals was usually characterised by only two parameters (Young's modulus E and a notional yield stress σ_y) and it became internationally entrenched in both investigations of structural behaviour and design calculations. Unfortunately, this two parameter model presents a problem for precise computational predictions of the strength both of individual members and of complete structures because it implies that finite length columns cannot attain the squash load, that the full plastic moment in bending cannot be exceeded and that other configurations involving compression elements of finite slenderness cannot strictly ever achieve full plasticity as they would theoretically require infinite ductility to do so (Fig. 1). By contrast, all experiments show that the true resistance systematically exceeds the fully plastic value in moderately stocky elements and structures, and this is usually only possible due to

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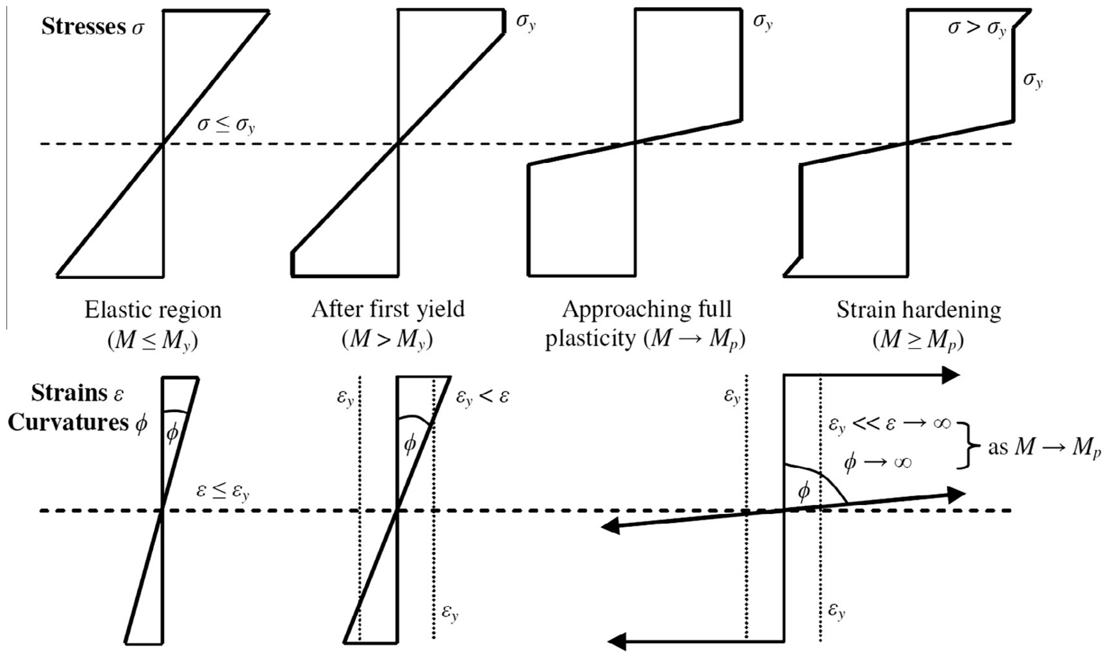

Fig. 1. Development of the stress and strain distributions under bending in a structural member: the full plastic moment M_p can only be attained with strain hardening.

strain hardening in the metal. Almost all current international design rules permit moderately stocky structures to attain a fully plastic state, but this is justified by empirical deductions from tests that are used to determine a limiting slenderness above which the full plastic resistance can no longer be attained.

The advent of computer evaluations of member strengths permitted much more sophisticated models of material behaviour to be used, but all computations relating to specific applications appear to have been based on an individual measure of the stress–strain curve obtained in the specific test series. It was tacitly assumed that what was measured in a particular series of laboratory tests would be relevant to all geometries and all international production of the same grade of steel. Unfortunately, current international standards for structural steel production do not define parameters other than the 0.2% proof stress, the ultimate tensile strength (UTS) and the elongation to rupture [8–14], so reliable and safe values for the strain hardening behaviour and yield plateau length are not commercially documented for any structural steel. If computer models are to be used to produce general recommendations for all structural elements, this situation poses a considerable challenge. When assessing the strength of stockier members and structures, it is difficult to be certain that any value derived from a single test series will produce safe estimates of the strength of all similar members. Thus it is not possible to produce safe and economical design calculations for all structures without a statistical review of existing measured steel stress–strain data.

In recent decades, experiments have become so expensive that computational modelling is more and more widely applied, and it is very difficult to justify the cost of experiments for every new investigation, especially for larger structural systems or studies where many variable parameters are involved. It is thus increasingly common that a heavy reliance is placed on computational predictions, but the safety of these calculations in the post-elastic range very much depends on the assumed ductility and strain-hardening properties. For carbon steels, the post-yield properties must include the length of the yield plateau. It is therefore critically important that more wide-ranging investigations of these post-yield properties are soundly grounded in statistical treatments. The range of structural forms, geometries, load cases and boundary conditions that require a reliable post-yield plastic characterisation is very wide and far beyond all currently available test evidence.

Uncertainties concerning the material strength are either treated in structural engineering limit state design through the concept of a ‘characteristic’ value, which is notionally statistically based and has a prescribed fixed probability of not being attained in a hypothetically unlimited series of tests [15,16], or an alternatively defined ‘nominal’ value [11,17] that has some other basis in experimental data. In either case, it is then multiplied by a ‘partial factor’ or ‘resistance factor’ that depends on the failure mode to obtain a ‘design’ value of the structure’s strength which is then used to achieve a desired margin of safety or reliability. Thereafter the entire design process is usually deterministic. Initiatives to develop fully probabilistic structural design methods do exist [18–20] and coefficients of variation on loads, geometry and material properties have been incorporated into AISI S100 [11] and AISC 360-10 [17] LRFD provisions amongst others, but there is currently insufficient data to establish the necessary statistical bounds on all required parameters. Moreover the design process would be very complex and too laborious for all but monumental structures and failure investigations. For example, the experimental JCSS Probabilistic Model Code [20] proposes to treat material properties as random variables subject to the laws of probability but currently considers only the yield and ultimate strengths, the elastic modulus, Poisson’s ratio and ultimate strain, with post-yield properties such as strain hardening and yield plateau length omitted due to a substantial lack of data [21].

A detailed study of over 40,000 mill test certificates of rolled wide flange (W), welded wide flange (WWF) and hollow structural (HSS) beam section samples mainly from ASTM A992 steels, representative of those most commonly produced for the US and Canadian markets [22], was performed by Schmidt and Bartlett [23,24]. These authors presented statistical relationships between the material properties (yield and ultimate strengths, modulus of elasticity) and geometric properties (flange/web thicknesses, web depths, diameter to thickness ratios) of these sections, and offered mean values and coefficients of variations on the most important material parameters as well as calibrating resistance factors for