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On the gradient of the yield plateau in structural carbon steels

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ABSTRACT

New design methodologies are being developed to allow stocky steel members to attain and exceed the full plastic condition. For theoretical validation, such methods require a characterisation of the uniaxial stress-strain behaviour of structural steel beyond an idealised elastic-plastic representation. However, the strain hardening properties of carbon steels are not currently guaranteed by the standards or by any steel manufacturer. Assumptions must thus be made on what values of these properties are appropriate, often based on limited information in the form of individual stress-strain curves. There is very little consistency in the choices made.

This paper first illustrates, using an example elastic-plastic finite element calculation, that a stocky tubular structure can attain the full plastic condition at slendernesses comparable with those defined in current standards and supported by experiment when using only a very modest level of strain hardening, initiated at first yield. It is then hypothesised that the yield plateau in the stress-strain curve for structural carbon steels, classically treated as flat and with zero tangent modulus, actually has a small but statistically significant positive finite gradient. Finally, a robust set of linear regression analyses of yield plateau gradients extracted from 225 tensile tests appears to support this hypothesis, finding that the plateau gradient is of the order of 0.3% of the initial elastic modulus, consistent with what the finite element example suggests is sufficient to reproduce the full plastic condition at experimentally-supported slendernesses.

1. Introduction

It has long been recognised that the full plastic moment of a cross-section cannot be attained at finite strains when assuming an ideal elastic-plastic representation of the stress-strain relation for the steel [1]. It is also very well established that tests on structural members show the reliable exceedance of the full plastic condition at finite slendernesses. In the past, this mismatch was frequently brushed aside by engineers because the focus was on the strength of single structural members for which test evidence was deemed sufficient and empirical rules based on member tests were used in design. However, in the modern world of innovative and complex structural forms, powerful software and limited budgets for testing, it is imperative that new design rules can be devised based principally on computational studies requiring only a minimum of empirical calibration. For this purpose, a reliable and safe characterisation of the post-yield material behaviour is essential. This paper seeks to establish such a characterisation.

Recent years have also seen the development of new design methodologies for steel structures such as the Generalised Capacity Curve [2–4], Reference Resistance Design [5,6] and the Continuous Strength Method [7,8] which formally permit the full plastic resistance of a structure to be attained and exceeded. Their development is based on significant advances in computational modelling that can now treat great structural and material complexities. However, to become an effective and widespread design tool, any such new methodology requires reliable knowledge of the post-yield strain hardening characteristics of the material. Unfortunately, these properties are seldom known with certainty, are not defined in any structural steel materials standard and are not guaranteed by any steel manufacturer.

A further consideration in the definition of the stress-strain relationship to be used for computational modelling is the issue of possible differences between results of a tensile control test and the behaviour of the steel in the structure. First, it is classically assumed that the tensile test also represents the compressive behaviour, which is more important because the structural behaviour for steel structures is dominated by stability considerations. Second, the tensile test, with its accurately machined boundaries, is free of the minor imperfections and variations in real structures that could well trigger the onset of Lüders bands and local yielding, preceding a more general yield state at a slightly higher mean stress. There are thus reasons to believe that the tensile test provides a conservative assessment of the material modelling that should be used for the best assessment of complete structures.

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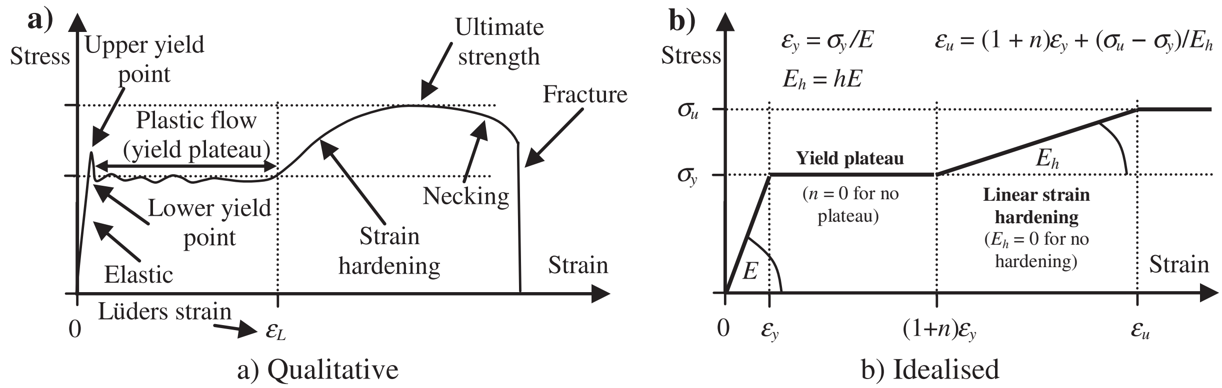

Fig. 1. Classic characterisations of a typical engineering stress-strain curve for structural carbon steel (after Sadowski et al. [16]).

There are many creative and innovative developments in the field of steel structures, with most involving structural systems rather than single structural elements, and the issues of ductility and stability being critical. In the past, the experimental testing of steel structures has relied heavily on single elements, transformed into design rules by statistically based empirical treatments and the results assumed to apply to complete structural systems. But testing is expensive, many different parameters affect the behaviour and the statistical treatment requires many 'identical' tests, so economy demands that computational modelling can be used instead to provide a safe justification. But such modelling is only safe if the material characterisation can safely and reliably define the early post-yield behaviour of the steel, since the competing demands of ductility and economy very commonly lead to small strain stability conditions. This forward-looking perspective is the key driver that led to the present study.

The engineering tensile stress-strain curve for structural carbon steels is classically characterised by three distinct regions. The first is linear elastic until to the upper yield point (Fig. 1a). After a small drop in stress to a 'lower yield' value, straining continues along a 'yield plateau' of plastic flow without any apparent change in stress: Lüders bands of plastic deformation propagate through the specimen [9,10]. When the whole specimen reaches the Lüders strain ε_L, further straining causes the stress to rise (strain hardening) and finally attains a maximum value (the ultimate tensile stress σ_u), after which necking leads to fracture. The length of the yield plateau depends on the manufacturing process and the strain history of the steel and is not an intrinsic material property. Its length is known to depend on the chemical composition, heat treatment, grain size and strain ageing, as well as on the test conditions of loading rate, specimen alignment and stiffness of the test rig [9, 11].

The stress-strain relationship has usually been simplified into an idealised piecewise-linear form (Fig. 1b), following one of three variants. The classical 'perfect elastic-plastic' variant requires only two material parameters, the nominal elastic modulus E_{nom} and the yield stress σ_y, and completely ignores strain hardening with a plateau tangent modulus $E_h = 0$ and an infinite yield plateau ($n \rightarrow \infty$). The second variant ignores the yield plateau ($n = 0$) but assumes that linear strain hardening E_h begins at the first yield strain $\varepsilon_y = \sigma_y / E_{nom}$, with the stress rising to the ultimate tensile strength σ_u. The value of E_h when $n = 0$ is open to debate, though 1% of the nominal elastic modulus E_{nom} is proposed by the Eurocode on plated structures EN 1993-1-5 [12]. The third variant is like the second but includes a finite-length yield plateau whose length n has been suggested to be up to 15 times ε_y (perhaps 1.5% strain) with E_h tangent moduli anywhere between 0.3% and 4% [13–15].

2. Scope of the present study

As was argued in an earlier study by the authors [16], very little evidence is usually offered by the structural analyst for a particular choice of material model, and this is reflected in a widespread inconsistency

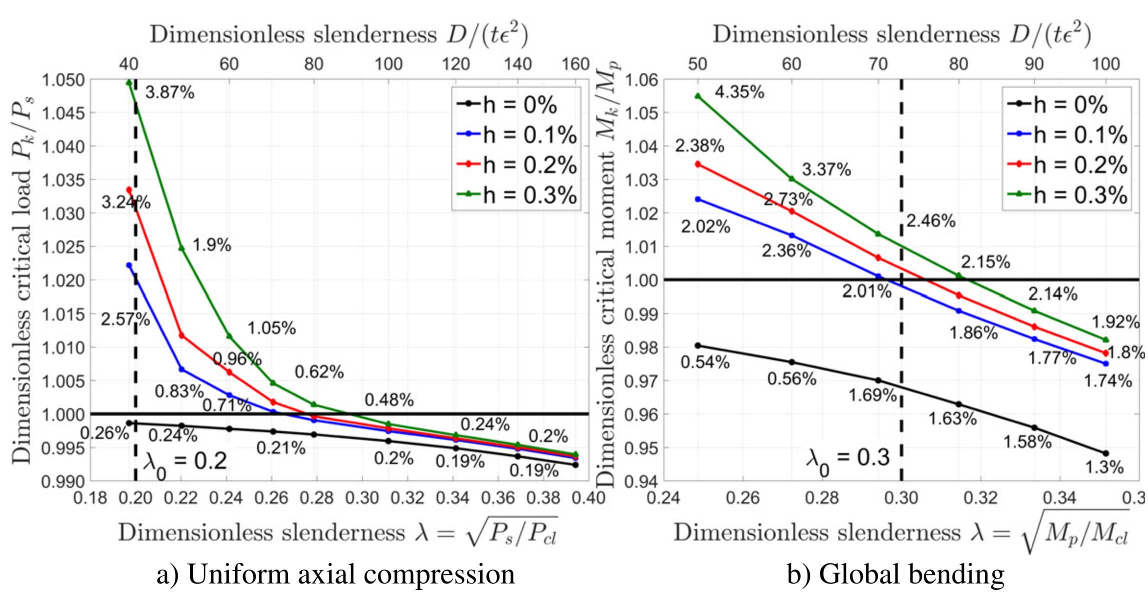

Fig. 2. The extreme stocky zone of capacity curves for perfect hollow circular tubes (Values in % denote the maximum compressive axial strain at the buckling load.).