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The effect of material stress-strain characteristics on the ultimate stress and critical buckling strain of flat plates subjected to uniform axial compression

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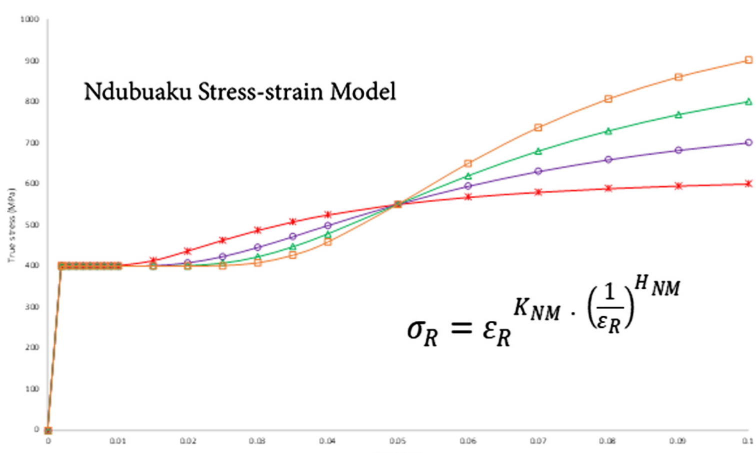
HIGHLIGHTS

- A novel and robust mathematical model for stress-strain approximation is presented.
- Strain-hardening is parameterized within the natural stress-strain space continuum.
- Buckling capacities of plates made of YPT materials are generally indistinguishable.
- Proportionality limit of plate material has significant effect on buckling capacity.

GRAPHICAL ABSTRACT



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ABSTRACT

The buckling capacity of uniformly compressed flat plates has been investigated in this study. Material properties were characterized based on parameterization of the stress-strain curves using a simple and novel mathematical expression. Idealized stress-strain relationships were developed using the proposed material model and extensive parametric numerical analyses were conducted to investigate the effect of the material stress-strain properties on the buckling capacity of flat plates. For stress-strain curves with a yield plateau, the results of the parametric study showed a minimal influence of the material properties on the buckling capacity of the plates whereas a significant effect of the strain-hardening properties was observed in plates with round-house curves. Ultimately, the proposed stress-strain model was shown to be remarkably useful for capturing the relevant intricacies associated with material nonlinearity when predicting the buckling capacity and post-buckling behavior of uniformly-compressed flat plates.

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Nomenclature

b	plate width
b_e	effective plate width
CHT	continuously-hardening type
CSM	continuous strength method
DSM	direct strength method
E	elastic modulus
E_o	Young's modulus
$E\text{-}PP$	elastic-perfectly plastic
H_{NM}	Ndubuaku model 'heel' parameter
K_{NM}	Ndubuaku model 'knee' parameter
N_u	longitudinally-applied uniform compressive force
t	plate thickness
UTS	ultimate tensile strength
YPT	yield-plateau type
YS	yield strength
β	slenderness ratio coefficient
ε_{pl}	proportionality limit strain
ε_R	constitutive model strain ratio
ε_u	ultimate strain
ε_{ult}	plate deformation capacity
ν	Poisson's ratio
σ_{cr}	elastic critical buckling stress
σ_{pl}	proportionality limit stress
$\sigma_{p,0.2}$	equivalent yield stress (corresponding to 0.2% plastic strain)
σ_R	constitutive model stress ratio
σ_u	ultimate tensile stress
σ_{ult}	plate load-carrying capacity (ultimate strength)
σ_y	plate material yield stress
$\sigma_{0.5}$	equivalent yield stress (corresponding to 0.5% total strain)
ω_{mn}	amplitude of out-of-plane deflection

1. Introduction

In many of the industrial or engineering applications where plates or plate elements are used, they are required to withstand diverse types of in-plane (compressive, tensile, shear, etc.) and/or out-of-plane (flexural, torsional, etc.) loading conditions.

Under operational conditions, one of the most common loading phenomena, which is of widespread concern, is the application of in-plane loads to two parallel edges of metal plates (uniaxial/longitudinal compressive or biaxial compressive and/or tensile loading). Where the expected compressive loads on a stiffened plate or plated structural member is significant, the compressive buckling resistance becomes of primary concern to the designer. Some of the main parameters which are generally considered in the design of axially loaded metal plates include the material properties, geometric properties (width/thickness ratio and aspect ratio) edge boundary conditions, and initial out-of-plane imperfections [1–3].

In various industrial applications and fields of engineering, there is an extensive use of moderately thick to thick plates thus introducing complexity in the approximation of the buckling capacity.[1] Besides the inclusion of shear deformation effects, increase in the thickness of compressive axially loaded plates increases the likelihood of inelastic buckling, especially in cases of plates whose uniaxial stress-strain behavior exhibits a relatively low proportionality limit stress compared to the nominal yield stress [4–12].

For almost two centuries, several researchers have investigated the elastic and inelastic buckling phenomenon in metal plates using various analytical, experimental, and numerical approaches, hence a considerable amount of information on the buckling capacity of metal plates is available. Specifically, various numerical and experimental investigations have been recently carried out to determine the buckling and post-buckling behavior of flat, simply-supported metal plates subjected to uniform compression. Rasmussen et al. [13] conducted two experimental tests on single plates cut from a 3 mm-thick UNS31803 stainless steel plate: the nominal widths were chosen as 125 mm and 250 mm, while the nominal length for the two plates was chosen as 750 mm. To simulate the post-buckling behavior of typical mild and higher strength steels used in marine structures, Mateus and Witz [1] developed numerical models for Grade B and API X52 steels respectively: the width of the plate models was fixed at 500 mm while they varied the slenderness ratio of the plate models between 0.5 and 6 and the aspect ratio was varied between 0.5 and 4. Bezkorovainy et al. [14] investigated the effect of material properties on the compressive strength of metal plates using an FE model similar to that used in Rasmussen et al. [13]: however, only square plates, with a width of 100 mm, were modelled in their study and the slenderness ratios were varied between 0.5 and 3. Paik et al. [15] studied the effects of shape, size (depth and diameter), and location of dents on the compressive capacity of dented simply-supported flat plates using the FE modelling approach: the width of the plate models was fixed at 800 mm, and five variations of the aspect ratio (1, 2, 3, 4 and 5) and three variations of the plate thickness (10 mm, 15 mm, and 20 mm) were applied. El-Sawy et al. [16] considered the problem of elastic and inelastic buckling of simply-supported perforated rectangular plates subjected to uniform compression using three grades of steel (A36, A572 Grade 50, and A572 Grade 60): two variations of the aspect ratio (1 and 2) were applied to the plate models while the b/t ratios were varied between 30 and 100.

Curve-fitting techniques are generally used to develop strength curve equations that correspond to experimentally and numerically obtained ultimate strengths. To determine the structural design resistance of metallic sections, a distinctive method of cross-section classification is generally used in most structural design codes. The cross-section classification approach is based on a *direct strength method* (DSM) [17,18] which relates the ultimate strength of a section to the overall cross-section slenderness. It is, however, based on the assumption of an elastic, perfectly-plastic material model which has been observed to be generalizable for structural sections made of carbon steel or any material with a yield plateau in its stress-strain response. For materials such as aluminum and stainless steel, which have a gradual yielding behavior and an absence of a distinct yield point, the direct strength cross-section classification approach tends to yield unduly conservative results hence, a deformation (strain) based design approach referred to as the *continuous strength method* (CSM) [19–21] is typically applied to relate the cross-section resistance to the cross-section deformation capacity such that the benefits of strain-hardening in the stress-strain response are accounted for. The measure of the cross-section deformation capacity is derived from the end-shortening corresponding to the ultimate applied load in the compressive axial load-deformation

[1] While in literature, the term "buckling behavior" is generally used in relation to the elastic critical buckling stress, the term "buckling capacity" is used, specifically within the context of this study, to refer to the methodological approximations of the ultimate compressive strength and corresponding uniform axial strain of flat plates subjected to uniform axial compression.