



Constitutive parameter calibration for structural steel: Non-uniqueness and loss of accuracy

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ARTICLE INFO

Article history:

Received 7 May 2015

Received in revised form 31 August 2015

Accepted 11 September 2015

Available online 16 September 2015

Keywords:

Finite element simulation

Constitutive models

Calibration

ABSTRACT

Finite element (FE) simulations used to characterize extreme limit states in steel structures require the calibration of numerous parameters. Calibration of these models for large strains (greater than 0.3 or so) cannot be performed using stress–strain curves on standard tests, since the stress state in these tests becomes non-homogenous due to necking or buckling which occur at lower strains. As a result, calibration is often performed by matching load–displacement curves of calibration specimens to those obtained through complementary FE simulations. In these situations, multiple parameter sets produce strain fields that match the measured load–displacement response, resulting in non-unique parameter fits. A series of 2400 FE simulations with 4 specimen geometries, 300 material parameters sets, and 2 loading histories indicates that multiple trial parameter sets produce excellent load–displacement match with the true material response, implying that the method is highly susceptible to non-unique fitting. All simulations use the Armstrong and Frederick constitutive model with a von Mises yield surface. The impact of non-unique fitting is assessed through FE simulations based on parameter sets that show excellent load–displacement match with calibration specimens. It is determined that the non-uniqueness does not significantly affect the prediction of peak force. However, it severely impacts the accuracy in prediction of internal plastic strains, with errors as large as 50% with respect to the true material. This has serious implications for FE simulation used to characterize extreme, strain-based limit states such as fracture. Strategies for mitigation of this inaccuracy are presented, along with limitations of the study.

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1. Introduction

Finite element (FE) simulation is commonly used to characterize extreme limit states in structural steel components. Sophisticated FE simulations have recently been used to characterize the response of structural steel braces, connections as well as steel plate shear walls [1–3]. More specifically, the various objectives of these simulations include modeling the load–deformation response of structures and components (e.g., [4]), characterizing internal stress and strain distributions, and predicting failure modes such as fracture, based on these internal distributions (e.g., [5]). There is increasingly heavy reliance on FE models to quantitatively determine extreme limit states, within a FE-simulation framework that seeks to describe structural performance accurately.

Accurate representation of material constitutive response (i.e., the relationship between the true stress and strain) lies at the heart of these simulations. This is particularly important if the limit states of interest are associated with high levels of inelasticity. Structural FE models that simulate these extreme limit states rely on multi-axial

cyclic plasticity models, which are able to simulate various aspects of material response including the Bauschinger effect, nonlinear isotropic and kinematic hardening, and ratcheting. For steel (and other polycrystalline metals), these constitutive models typically employ a von Mises yield surface, and the assumption of isochoric plastic flow (wherein volume is conserved during plastic deformation) [6]. Some popular models used to simulate the inelastic response of steel include the bounding surface model [7], and the Armstrong–Frederick (AF) model [8]. To replicate the various phenomena discussed above, these models require the calibration of numerous (≈ 4 –10) parameters. The accurate calibration of these parameters is a challenging process for two reasons. First, standard uniaxial coupon specimens (ASTM E8 [9]) such as shown in Fig. 1a (referred to henceforth as Cylindrical Tensile, or CT specimens) are ideal for calibrating “engineering” material properties such as yield stress to be used in design. However, these standard tests are able to produce a homogenous stress state in the specimen only prior to unstable necking, which initiates at strains on the order of 0.1–0.2 (i.e. 10%–20%) — e.g., see [10]. After this, the localized (necked) specimen response is controlled by interactions between material hardening and the change of geometry. In this regime of loading, the strain and stress states are non-homogeneous, such that higher strains (as well as increased stress triaxiality or constraint) are encountered towards the center of the

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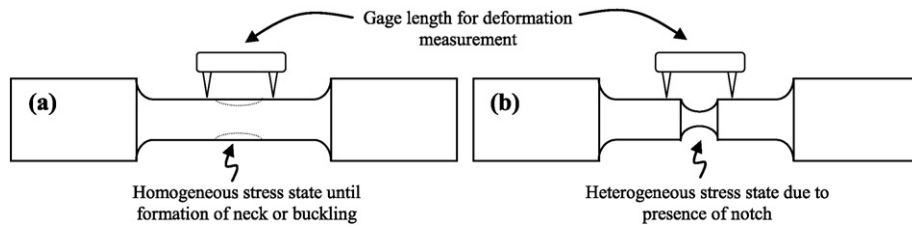


Fig. 1. Commonly used calibration coupons: (a) CT – Cylindrical Tension (b) CNT – Circumferentially Notched Tension.

necked region. Bridgman [11] has examined this type of post-unstable-necking response extensively.

A similar problem is encountered for cyclic loading (which may be used to calibrate parameters associated with cyclic hardening), such that compressive strains on the order of 5% (or even less) produce specimen buckling, thereby limiting the strain amplitudes that may be applied homogeneously to the specimens [12]. As a result, standard coupon tests are ill-suited for calibrating model parameters where the end application is characterizing material response over larger strain ranges (i.e., strain greater than ≈ 0.2). However, response of real structural components is often controlled by larger strain ranges over local regions (on the order of 0.8–1.0 prior to fracture; refer [13], and on the order of 0.3–0.4 prior to local buckling in tubular braces; refer [14]). The implication is that parameters calibrated from standard coupon tests cannot be appropriately applied for the simulation of structural components.

To overcome these issues, a commonly used strategy [15–17] is to calibrate the material model parameters directly from the *load–displacement curve* of the specimen, rather than the *stress–strain* response. This involves the construction of finite element models complementary to (i.e., which replicate) the test specimen. The material parameters themselves are then calibrated indirectly through trial and error, by matching the load–displacement curve of the simulation to that obtained from the tests. Specimens used for this type of calibration may include CT specimens shown previously in Fig. 1 (complemented by FE simulation of the post-unstable-necking response with non-homogeneous strains) or circumferentially notched tension (CNT) specimens (Fig. 1b) into which a sharp inhomogeneity can be introduced in a controlled manner, or other specimens, loaded in monotonic or cyclic loading.

While attractive at first glance, this approach introduces additional sources of inaccuracy and uncertainty. The main underlying problem is that the load–displacement curves are the result of complex interactions between the material response (e.g. hardening) and geometric nonlinearity (such as localized necking or buckling). As a result, it may be argued that the inverse problem of calibrating material parameters from load–displacement curves is ill-posed in general, since infinitely many deformation fields are admissible within the applied boundary conditions (i.e. the load and displacement response measured at the boundaries), and that these fields depend on the constitutive response. Other researchers [18–20] have identified the ill-posed nature of this problem, recognizing that it renders the calibration susceptible to non-unique parameter fits. This means that many sets of calibrated parameters may closely (or exactly) match the load–displacement data from the tests. The specific implications of this in the context of structural modeling are the following:

1. Since multiple constitutive parameter fits are theoretically possible for a set of load–displacement calibration test data, these are liable to producing dissimilar load deformation response for *application* components that are dissimilar (in terms of stress distribution or loading history) as compared to the calibration data set. Moreover, it is impossible to determine a priori which of these parameter sets is the appropriate representation of constitutive response. This implies that the predictions of response based on the calibrated parameters are non-robust.

2. As discussed above, the non-unique fits are a result of multiple admissible strain fields within the applied boundary conditions. As a result, application simulations based on these fits may result in different strain fields (even if the load deformation response is not different). This has adverse implications when the stress/strain fields are used for prediction of fracture or other damage states utilizing criteria such as Stress Modified Critical Strain – SMCS [21] or the Void Growth Model [22].

Motivated by these issues, the main objectives of this paper are:

1. To quantitatively examine the susceptibility of common calibration specimens (such as shown in Fig. 1a and b) and procedures, to inaccuracies arising due to the above mentioned non-uniqueness of constitutive parameter calibration for structural steels.
2. To quantify the effect of this non-uniqueness on performance prediction (i.e. simulation) of limit states (such as load deformation response, peak loads and critical strains) in structural steel components.
3. Based on (1) and (2) above, to characterize the inaccuracy in the simulation of structural steel components with the ultimate objective of providing support for methods and best practices to mitigate this inaccuracy.

It is emphasized here that the purpose of the paper is not to develop or refine a material constitutive model, or to assess the efficacy of an existing material model against experimental data. The purpose of the paper is to *assess the process* by which constitutive models are calibrated, and provide suggestions for enhancing these processes. The paper begins by summarizing the methodology of the research, which is based on a set of 2400 FE simulations. The simulations use a variant of the Armstrong and Frederick [8] constitutive model, and examine various strategies and tolerances for calibration, and the effect of these strategies on the accuracy of results. A critical analysis of the factors underlying the observed issues is then presented. The paper concludes by summarizing the results, and suggesting optimal strategies for robust calibration.

2. Methodology

Fig. 2 schematically illustrates the methodology used to achieve the objectives outlined above. A brief overview of the methodology is first presented, followed by details of each component within it. The methodology relies on the notion of a “true” material, and the precept that the purpose of calibration is to determine material parameters by matching the load–displacement curves of FE simulations of calibration specimens using trial parameters to the load–displacement curves of identical specimens which feature the true material. For the purposes of this study, a “true” material is generated synthetically, followed by the generation of 299 trial parameter sets. Finite element simulations of various specimen types (discussed later) are conducted with the true material, as well as the trial parameter sets. In this way, trial parameter sets that produce an acceptable match with the true load–displacement curves (within specified tolerances) are identified. Analysis of these acceptable trial parameter sets is used to develop insights regarding the potential for non-unique fitting. Finally, the trial parameter sets are used to predict structural performance metrics (such as peak load and internal

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