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Numerical simulation of the high strain-rate behavior of quenched and self-tempered reinforcing steel in tension

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ABSTRACT

This paper presents the numerical analysis of the high strain-rate behavior of quenched and self-tempered reinforcing steel in tension. The investigation has been performed properly simulating the experimental facility (SHTB-Split Hopkinson Tension Bar), highlighting criticism in the simulation and interpretation of the experimental results. Finite element simulation has allowed a robust model validation of the B450C reinforcing steel. Parametrical finite element model has been used to rebuild the input and output signals of the SHTB. Physical influence of damping in input wave and modeling strategies have been discussed. The elastic and damping dispersion fonts have been introduced into the model to explain the real case variability in SHTB signals. Strain-rate dependent plasticity model has been used by LsDyna code features. Time dependent plasticity has been developed to explain upper and lower yield values of the material resulting into a loading rate sensitivity. Finally, the material model has been used to reconstruct a virtual test over a rebar of 32 mm diameter, as an example of general procedure to calculate the global material response.

1. Introduction

The understanding of the dynamic behavior of concrete and reinforcing steels is essential for the precise assessment of existing reinforced concrete structures when they are subjected to a high loading rate. These assessment studies are usually conducted by means of finite element codes and the material models have to be properly based on correct experimental data. The difficulties connected to the complexity of the experimental tests can be appropriately understood and solved by numerical simulation. To better comprehend the experimental results it is essential to perform the simulation of the testing machine [1–5] in order to obtain mutual verification.

In the analysis of the experimental results often it is possible to face difficulties in interpreting the results due to the presence of instabilities (i.e. presence of the first peak), which are not considered in the usual material constitutive laws as Johnson–Cook [6].

These instabilities are due to the upper and lower yield stress of the material and have been investigated by several authors. The upper yield stress has been explained with metallic structure parameters such as the dislocation density and velocity [7]. In any case, material models involving microstructure parameters are not suitable for engineering purposes. Structural assessment requires relations between the upper and the lower yield value with the engineering variables associated to the loading pulse, structure geometry, stress and strain tensor. Models that require the definition of material variables in terms of structure and dislocation density/velocity can be considered a phenomenological explanation of upper yield lacking of the complete parameterization of the stress strain curve including upper, lower yield and its time dependencies.

Engineering investigations of upper yield were made by Campell and Harding [8–10]. Campbell introduced the delay time and thermal activation theory by which the upper yield occurs after a characteristic time after the start of the loading stress due to the shear band thermal activation [11].

The value of the upper yield stress was further investigated by Harding [12], who introduced a linear relation between dynamic upper yield stress enhancement and loading rate. Harding's approach is the most suitable engineering formulation for upper yield found in the literature.

The experimental study of the dynamic tensile behavior of full-scale quenched and self-tempered rebar (16–40 mm in diameter) is practically impossible, except maybe in the case of very large facilities (i.e. the large facility of the Joint Research Centre, Ispra). The unfeasibility of this study has led us to proceed to the characterization of the material [13] and the numerical analysis of the dynamic behavior of the material with the present paper. The importance of the numerical simulation is definitely based on the possibility of studying real scale structural elements by means of numerical simulation of tests otherwise not feasible for

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technical or economic reasons. The present work completes, from a numerical point of view, what was started [13] with the experimental one, analyzing the various critical aspects regarding both experimental technique used and numerical simulation.

The experimental technique used for the high strain rate mechanical characterization of B450C rebar was the Split Hopkinson Tension bar (SHTB) and was described in [13–15]. In this particular set-up the input pulse is not generated by a striker who hits the input bar, as in the traditional Split Hopkinson Pressure bar, but using the energy stored in a pre-stressed bar directly connected to the input bar [16].

This set-up offers several advantages compared to the traditional one, avoiding problems connected to the planar impact between striker and input bar, to the pulse length, etc.

The numerical analysis has been performed properly simulating the SHTB, highlighting criticism in the simulation and interpretation of the experimental results.

This paper is organized as follows. Section 2 presents the criticisms of the SHTB. Section 3 reports the numerical model of the experimental set-up. The numerical model results are presented in Section 4 both in terms of FEM and numerical analysis. These results are discussed in Section 5. The model of the real size rebar is presented in Section 6. Finally, Section 7 summarizes the whole work.

2. Critical aspects of the Split Hopkinson Tension Bar

2.1. Signals analysis

Signal analysis is usually adopted in the traditional theory of the Split Hopkinson Bar (SHB) to calculate stress, strain and strain-rate [17]. Another methods consists in the combined use of the simulation and experimental test data. The validation of material model is then made by numerical and experimental gauge signal comparison.

The advantages in combined use of simulation and experimental data are: (i) accurate final material model verification; (ii) specimen geometrical non linearity is included; (iii) the hypothesis of uniformity of stress/strain through the specimen is overcome; (iv) inertial effects are included; (v) multi material and small structure specimen can be investigated; (vi) possible use of simulation for experimental facilities accuracy enhancement; and (vii) optimization techniques and sensitivity analysis can be applied.

2.2. Effect of perturbations into the signal

SHB relations contain several idealizations as the one-dimensional wave propagation through bars and specimen, the uniformity stress in the specimen, the absence of perturbations and inertial effects. It is well-known as a real input signal of SHTB differs from the ideal trapezoidal pulse due to local perturbations when the real signals are used to obtain the material model parameters, a series of errors are included due to simplified hypothesis and signal perturbations. The study of perturbed real signal effects to material model response is suitable to enhance the material model correctness. The influence of these factors on the material model response can be checked by means of finite element simulation.

The input signal is mainly characterized by amplitude, duration, and rising time. These main characteristics can be adapted to generate the wanted dynamic loading conditions into the specimen reaching the wanted rate during the experiment.

The wanted input amplitude and duration are generated by tuning the physical parameters of the input pulse generation method (striker or pre-stressed bar).

The input stress rising time is another significant characteristic for the material response and it is conditioned by the SHB set up (striker or pre-stressed bar), by the use of pulse shaper, and by other physical parameters out of direct control such as the facilities damping.

The pulse shaper technique [17,18] is generally applied to smooth the input signal, in case of stress oscillations typical of striker impact in SHB. By interposition of an intermediate deformable element between striker and input bar, a higher repeatability and a smooth input pulse is obtained. If short rising time is wanted, the input signal will be also affected by high frequency perturbations, especially in SHB configurations. High frequency perturbations widen the repeatability of signals and are subject to the elastic and damping dispersion phenomena. Usually in SHB a ratio length/diameter is adopted, which is always suitable to elastic and damping dispersion [17]. The damping influences the input dispersion and its effect should be evaluated such as the elastic dispersion.

Damping is not directly controlled in SHB. Different facilities could generate pulses with significant differences in rising time and perturbations.

Referring to Fig. 1, three typologies of input signal could be generated:

1. Low loading rate, high rising time, no apparent wave dispersion (curve a).
2. High loading rate, dispersion with hypercritical damping (curve b).
3. High loading rate, dispersion with sub critical damping (curve c).

When a high loading rate is wanted to study loading rate dependent materials, input signal (b) or (c) has to be generated.

The phenomena which generate the pulse perturbations can be grouped as:

- Unlocking(SHTB)/contact(SHB) perturbations/combined use of shaping technique.
- Pochhammer–Chree wave dispersion [19,20].
- Damping effects/damping dispersion.

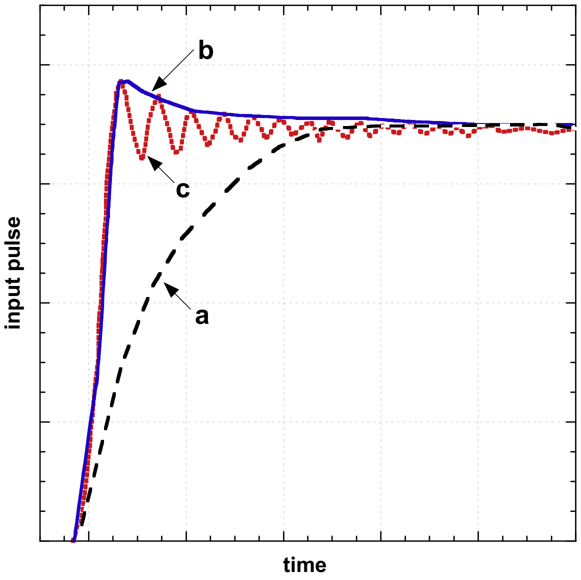

Fig. 1. SHB input pulse in the case of: (a) pulse shape technique is used; (b) dispersion and over critical damping; and (c) dispersion and sub critical damping.