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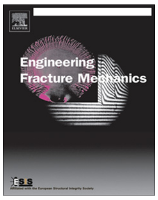

Fracture of eutectoid steel bars under tensile loading: Experimental results and numerical simulation

Fernando Suárez [a], Jaime C. Gálvez [b,*], David A. Cendón [c], José M. Atienza [c]

[a] Departamento de Ingeniería Mecánica y Minera, Universidad de Jaén, Campus Linares, 23700 Linares, Jaén, Spain
[b] Departamento de Ingeniería Civil: Construcción, E.T.S de Ingenieros de Caminos, Canales y Puertos, Universidad Politécnica de Madrid, C/ Profesor Aranguren, s/n, 28040 Madrid, Spain
[c] Departamento Ciencia de Materiales, E.T.S de Ingenieros de Caminos, Canales y Puertos, Universidad Politécnica de Madrid, C/ Profesor Aranguren, s/n, 28040 Madrid, Spain

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ABSTRACT

Construction steel bars tested under tension usually show a cup-cone fracture pattern. Nevertheless, some steels, such as the eutectoid one used for manufacturing prestressing steel wires, show a different pattern: a flat fracture surface with a dark region inside. This paper presents experimental work performed to identify the fracture mechanisms that trigger this particular flat fracture pattern and numerical simulations where it is reproduced numerically. The experimental tests are carried out on cylindrical specimens of three diameters, 3, 6 and 9 mm, subjected to tension. In order to analyse the fracture mechanism, numerical simulations are performed by using the finite element method and the cohesive zone approach. To that end, a cohesive interface element with mechanical properties that depend on the stress triaxiality is presented and assessed. This approach provides reasonably good agreement with the experimental results. In addition, when compared with other popular models such as the GTN model, it presents certain advantages since it requires a smaller number of parameters to be defined.

1. Introduction

Steel, together with concrete, is the most widely used material in construction works. Both its high strength and ductility make it especially interesting from the structural safety point of view. This is because under extreme accidental loads it enables stress redistribution with adjacent elements that allows more energy to be dissipated before reaching the structural failure. However, despite being extensively used, there remain certain aspects related to its fracture behaviour that deserve to be clarified and that may allow a better use of its properties in the future.

Because of its simplicity tensile testing is the most extended method for the measurement of the mechanical properties of steels. This method is standardised [1,2] and allows the stress–deformation curve of the material to be obtained. When a steel item is tested under tension and reaches the maximum stress point, a necking process begins and makes it difficult to define the material behaviour from that moment onward. Indeed, because of these difficulties, the last part of the stress–deformation curve that goes from the maximum load point up to fracture is usually neglected when, in the authors' opinion, it contains interesting and valuable information related to structural safety.

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[*] Corresponding author. Tel.: +34 913365350.
E-mail address: Jaime.galvez@upm.es (J.C. Gálvez).

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Nomenclature

Lower case

f_c	critical void fraction
f_t	tensile strength (MPa)

Upper case

F	force (N)
F	factor dependent on the stress triaxiality factor (T)
G_F	cohesive fracture energy (N/m)
GTN	Gurson–Tvergaard–Needleman model
J_e	Jacobian matrix
L	gauge length
SEM	scanning electron microscope
T	stress triaxiality factor

Greek

ε	strain
σ_{H}	spherical part of the stress tensor (volumetric stress)
σ_{VM}	Von Mises equivalent stress

The necking process leads to fracture in the thinner section of the necked region and, when testing cylindrical specimens, usually takes place with the typical cup-cone surface pattern, like that shown in Fig. 1.

The fracture of ductile metals, including construction steels, has usually been explained with the theory of nucleation, growth and coalescence of microvoids. According to this theory, at a first stage and under high stress levels, microvoids are developed inside the material (nucleation) due to a decohesive process of small inclusions that are torn apart from the rest of the material or by the fracture of the particle that constitutes the inclusion itself. At a second stage, and under higher deformational states, these microvoids increase their size (growth) until they become interconnected (coalescence) [3]. Such a process weakens the material until its eventual failure. This theory has formed the basis of several numerical models that have sought to reproduce the fracture on ductile materials, with the Gurson model being the most popular of them [4]. The formulation of this model is based on the behaviour of a spherical void inside an incompressible material under different loading states, studied by Rice and Tracey [5]. Since its appearance, Gurson-type models have been applied to various ductile materials, such as aluminium, copper and steel. The subsequent evolution of the Gurson model, proposed by Tvergaard and Needleman, has reproduced not only softening due to the growth of microvoids, but also eventual fracture of the material [6]. In fact, many variations of the Gurson–Tvergaard–Needleman (GTN) model have been proposed since its appearance in 1977, adapting its formulation with additional parameters, such as temperature [7], and correcting its behaviour under different triaxiality states [8–10].

As previously mentioned, the main advantage of GTN models is that their formulation is based on the physical process that explains the fracture mechanism: nucleation, growth and coalescence of microvoids. Despite its success when modelling the fracture behaviour of many ductile materials, GTN models have two principal disadvantages:

- The first involves the many parameters needed to define the model, which makes it difficult to obtain a valid set of parameters. Furthermore, as Steglich et al. state [11], there is not a single set of valid parameters and different sets can be suitable in reproducing the same experimental result.
- The second involves certain parameters required by the model that cannot be obtained experimentally. For instance, the critical void volume fraction, f_c, is defined as the critical void fraction required for the coalescence process to begin, which cannot be measured by experimental procedures.

These disadvantages do not allow the parameters of the model to be defined *a priori* and lead to a trial-and-error sequence that provides a set of parameters that is able to reproduce experimental results but is not unique.

On another note, although cup-cone fracture is typical of tensile failure in metallic materials with a ductile behaviour, not all construction steels exhibit this fracture pattern. Fig. 2 shows the fracture surface of a cylindrical specimen of pearlitic steel, used for manufacturing prestressing steel wires. This type of steel presents a flat fracture surface, perpendicular to the loading direction and with a dark region in the centre of it. Regarding this fracture pattern, the following hypothesis is proposed in this paper: the central dark region is the result of a process of nucleation and growth of microvoids, causing