Engineering Fracture Mechanics 140 (2015) 1–16

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

# Influence of the softening curve in the fracture patterns of concrete slabs subjected to blast

G. Morales-Alonso [a,*], D.A. Cendón [b], F. Gálvez [b], V. Sánchez-Gálvez [b]

[a] E.T.S.I. Industriales, Universidad Politécnica de Madrid, c/ José Gutiérrez Abascal, 6, 28006 Madrid, Spain
[b] E.T.S.I. Caminos, Canales y Puertos, Universidad Politécnica de Madrid, c/ Profesor Aranguren, s/n, 28040 Madrid, Spain

ARTICLE INFO

*Article history:*
Received 15 July 2014
Received in revised form 12 February 2015
Accepted 19 March 2015
Available online 26 March 2015

*Keywords:*
Explosions
Reinforced concrete
Cohesive crack model
Quasi-brittle materials
High strain rates
Numerical simulation

ABSTRACT

Reinforced concrete elements subjected to blast may present shear failure modes different to those expected under static loading. Shear failure under impulsive loading is caused by the fracture of concrete under tensile stresses, a topic which has not been thoroughly assessed under high strain rates. This research sheds light on this issue, through the experimental results provided by the authors and an own-developed constitutive model for the simulation of concrete under blast loading, based on the Cohesive Crack Model. Findings point out the importance of the shape of the softening curve of concrete in the development of different failure modes.



## 1. Introduction

Buildings and other kind of structures may be exposed to explosions due to both terrorist attacks and accidents during their service life. These kinds of threats may cause the destruction of one or several of the structural members of the building's bearing structure, inducing significant deterioration or even its total collapse. Given the fact that reinforced concrete is the most widely used building material because of its good mechanical properties, moldability and production economy, the behavior of reinforced concrete elements when subjected to explosions is a topic of major concern for researchers, engineers and security agencies.

However, the assessment of the structural response when the loading action is of an impulsive type is a challenging task, as the structure cannot be considered as responding globally and simultaneously to the blast action. That is, local failure of structural elements has to be accounted for. This is a major issue, since local failure in some structural elements is the actual cause of progressive collapse of the structure, with catastrophic consequences for its occupants [1]. Furthermore, structural elements have been reported to fail in a different way when subjected to highly dynamic loads than what would be expected under static loading. In particular, shear failures on elements subjected to bending have been found in [2–5]. This is a brittle mode of failure that severely limits the load capacity of an element, making the structure even more prone to progressive collapse.

Given the fact that concrete is a material of a quasi-brittle nature, the failure mode of reinforced concrete structural elements is highly influenced by concrete fracture mechanics and, more specifically, by the mechanisms of fracture in tension.

* Corresponding author.
*E-mail address:* gustavo.morales@upm.es (G. Morales-Alonso).

http://dx.doi.org/10.1016/j.engfracmech.2015.03.035
0013-7944/

**Nomenclature**

| | |
|---|---|
| $A$ | yield stress for the Johnson–Cook constitutive model |
| $B$ | strain hardening multiplier for the Johnson–Cook constitutive model |
| $C$ | strain rate hardening factor for the Johnson–Cook constitutive model |
| DIF | Dynamic Increase Factor |
| DIF $G_F$ | Dynamic Increase Factor for specific fracture energy |
| $f(\ )$ | softening curve function |
| $f_{ct}$ | concrete tensile strength |
| $f_{ctd}$ | concrete tensile strength under high strain rates |
| $G_F$ | specific fracture energy |
| $m$ | thermal softening exponent for the Johnson–Cook constitutive model |
| $n$ | strain hardening exponent for the Johnson–Cook constitutive model |
| $P$ | load applied on a pure tensile test |
| $\mathbf{t}$ | traction vector across the crack lips |
| $T^*$ | homologous temperature in the Johnson–Cook constitutive model |
| $\mathbf{w}$ | crack opening vector |
| $w$ | crack opening width |
| $w_{ch}$ | characteristic crack opening width |
| $\widetilde{w}$ | normalized crack opening parameter |
| $Y_{JC}$ | yield stress in the Johnson–Cook constitutive model |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | parameter used in the definition of DIF according to CEB |
| $\beta$ | parameter used in the definition of DIF according to CEB |
| $\delta$ | displacement of the sample end on a pure tensile test |
| $\bar{\varepsilon}_p$ | equivalent plastic strain in the Johnson–Cook constitutive model |
| $\dot{\bar{\varepsilon}}_p^*$ | dimensionless plastic strain rate in the Johnson–Cook constitutive model |
| $\dot{\varepsilon}$ | strain rate |
| $\dot{\varepsilon}_0$ | threshold of static strain rate |
| $\sigma$ | stress transferred across the crack |
| $\sigma_I$ | maximum principal stress |

Blast waves due to an explosion will generally not cause the crushing of concrete under compression, except in the case where the explosive is attached to a structural element. In other words, failure of concrete elements subjected to blast loading seems to be caused primarily by tensile stresses.

Fracture mechanics is one of the most commonly used methodologies for predicting the tensile behavior of concrete elements. Fracture of concrete has been examined by using different methods. Among them, the Cohesive Crack Model has proved to be the most versatile and accurate. It was firstly applied to concrete by Hillerborg et al. [6]. In comparison with previous approaches to the fracture of concrete, the model proposed by Hillerborg was the first to succeed in explaining the apparent dependence of fracture toughness on size that was found in the first attempts of applying Linear Elastic Fracture Mechanics to concrete specimens [7,8]. Since then, it has been extensively used to model crack initiation and growth in concrete, particularly under static conditions and different loading modes [9–15].

The cohesive crack model is composed of three main ingredients, (i) the tensile strength of the material, which is the maximum principal stress at which material cracking initiates, (ii) the specific fracture energy, which represents the amount of energy necessary to fully open a unit area of cracking and (iii) the softening curve, which rules the tensile strength degradation as the cohesive crack opens. An extensive review of the cohesive crack model can be found in [16].

The cohesive crack model was originally developed for modeling the behavior of concrete and other quasi-brittle materials under static loading. It has proved its reliability in that domain, providing realistic results for a number of experimental programs. However, it is well known that concrete behaves differently when subjected to impulsive or highly dynamic loading, that is, high strain rates. Over recent decades, the strain rate sensitivity of the three aforementioned ingredients of the cohesive crack model has been addressed by researchers to different extents, as described below.

Tensile strength is one of the most common parameters found in the literature on the influence of high strain rates, as in the studies [17–20]. It has been stated that the tensile strength of concrete is enhanced under high strain rates, and several formulations for this strength increment have been proposed, as in [21–23].

With regard to the specific fracture energy, there appears to be a lack of agreement among the scientific community, perhaps due to the complexities associated with performing such measurements under dynamic conditions. Classical results from Zielinski [24] pointed to maximum increases in the Dynamic Increase Factor (DIF) for fracture energy between 6 and 8 at loading rates of 30 GPa/s. More recently, tests using the Split Pressure Hopkinson Bar (SPHB) [25–27] and a