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Tensile behavior of concrete under high loading rates

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A B S T R A C T

The experimental and theoretical studies show that the influence of loading rate on tensile behavior of concrete is relatively strong. Dynamic tensile resistance of concrete is difficult to measure by direct tensile test. Therefore, the indirect tensile tests such as split Hopkinson bar tests are used. The evaluation of experimental measurements shows that after reaching a certain critical strain rate, tensile resistance progressively increases with increasing strain rate. In this paper, the authors attempt to investigate and discuss: (i) the reason for progressive increase of tensile resistance beyond a certain strain rate and (ii) whether the dynamic resistance can be attributed only to material strength or whether some other factors also contribute towards the same. To answer these questions, numerical analysis on two different types of examples is carried out: (i) Simple elastic-cohesive finite element (FE) model subjected to direct tension and (ii) FE model of indirect tension test on modified split Hopkinson bar. The results are evaluated in terms of apparent and true strength and compared with experimental results. It is found that under static loads, the true and apparent strengths are always equal, while under dynamic loads they are different. The true strength is controlled by the rate dependent constitutive law and the apparent strength is significantly influenced by the size of the fracture process zone and the size of the specimen. Evaluation of numerical results shows that concrete fracture energy is approximately a linear function of strain rate (semi-log scale) and is controlled by the rate dependent constitutive law. It is concluded that the results of any indirect tension test such as split Hopkinson bar test need careful interpretation, i.e. due to the fact that concrete specimen is damaged, and not elastic, the results of measurement need to be corrected.

1. Introduction

Several experimental [1–9], theoretical [10–13] and numerical [14–23] studies have shown that loading rate significantly influences the resistance and failure mode of concrete structures. In linear elastic materials or within linear elastic range no rate sensitivity can be observed, while, in case of materials that exhibit damage and fracture phenomena, such as concrete, there is significant influence of loading rate on strength and structural response. This indicates that rate sensitivity might be closely related to damage and softening of the material, i.e. more damage, the stronger will be the influence of loading rate on structural response. This is confirmed by experimental results which show that concrete-like materials exhibit the highest rate sensitivity whereas brittle materials (e.g. glass) are much less sensitive to the strain rate [3].

The response of concrete structures depends on time dependent loading through three different effects [17,18]: (1) through the rate dependency of the growing micro-cracks (influence of inertia at the micro-crack level), (2) through the viscous behavior of the bulk material between the cracks (creep of concrete or viscosity due to the water content) and (3) through the influence of inertia forces, which can significantly change the state of stresses and strains of the material. When modeling concrete in the framework of meso- or macro-continuum, the first two effects can be accounted for by the constitutive law and the third effect should be automatically accounted for through dynamic analysis where the constitutive law interacts with inertia. Depending on the material type and loading rate, the first, second or third effect may dominate. For quasi-brittle materials, such as concrete, the first two effects are important for relatively low and medium strain rates. For higher strain rates (impact) the last effect dominates, however, the rate dependency cannot be neglected.

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The experimental evidence shows that concrete exhibits the strongest influence of loading rate under tensile load [24]. The evaluation of experimental results, under assumption that concrete before tensile cracking is linear elastic, show that after reaching a certain critical strain rate tensile resistance progressively increases with increasing strain rate. To experimentally study the uni-axial tensile behavior of concrete is difficult even under static load. Therefore, indirect methods such as Brazilian test, compact tension tests, etc. are often employed. Moreover, it is very difficult to evaluate the direct dynamic uni-axial tensile behavior of concrete even numerically, since at high loading rates the failure always occurs locally, near the loading points. Therefore, under dynamic loads, the problem is studied through indirect tests such as split Hopkinson bar tests [6,21,25].

Typically, in the split Hopkinson bar test, the measurement of concrete strength is based on the theory of uni-axial (one dimensional) wave propagation through elastic media and measurements of strain and strain rates in the bar. The results of experiments [24] show that for strain rates lager than approximately 1/s the resistance increases progressively with the increase of strain rate. The questions that arise are: (i) what is the reason for such an increase and (ii) whether the experimentally measured resistance can be attributed only to the material strength or there are some other effects that need to be considered when evaluating results of experimentally measured data.

Though the split Hopkinson bar tests are widely used for determining the dynamic compressive and tensile strength for concrete, there are certain issues that are still unclear to the researchers. Wu et al. [26] commented that the SHPB results are reliable only for ductile materials such as metals, whereas the results may contain significant errors when measurements are made using SHPB on concrete-like materials. Li and Meng [27] reported that the apparent dynamic strength enhancement beyond the strain rate of 100/s is strongly influenced by the hydrostatic stress effect due to the lateral inertia confinement in an SHPB test. They further strongly commented that this apparent dynamic strength enhancement has been wrongly interpreted as strain-rate effect and has been adopted in both dynamic structural design and concrete-like material models for analytical and numerical simulations, which may lead to over-prediction on the dynamic strength of concrete-like materials [27]. Based on their study, which was primarily based on investigating the dynamic compressive strength of concrete, they recommended further experimental and numerical studies to understand the genuine strain rate effects.

The contribution of inertia in leading to the rise in concrete compressive strength under dynamic loading is well acknowledged and generally acceptable [26–35]. Though, the influence of inertia on tensile strength is not so well-accepted as that on compressive strength, recent experimental and numerical studies show a very high contribution of inertia on the tensile strength beyond a certain strain rate [18,36–38]. Based on numerical work supported by theoretical equations, Cusatis [36] reported that the contribution of the inertia forces to the tensile DIF is about ten times bigger than the contribution of the inertia forces to the compressive DIF. He also commented that experimental data showing significant difference in the compressive and tensile DIF are fitted very well by the numerical model if inertia effects (as well as other structural features of the tests such as specimen geometry and boundary conditions effects) are included in the numerical simulations [36]. Weerheijm and Van Doormaal [37] reported that it is possible that even in case of notched specimens, at the high loading rates the inertia effects dominate the failure process and stress concentrations have a minor effect on the observed specimen strength. They commented that detailed numerical modeling is needed to quantify the effect. Cotsovos and Pavlovic [38] suggested that under dynamic tests the concrete specimen must be viewed as a structure since its behavior is directly linked to the inertia effect of its mass and the boundary conditions. It has been shown by several examples [18,36,38,40] that the approach where the material properties is not artificially modified to consider the steep rise in DIF and considering the inertial effects leads to realistic simulation of the dynamic tensile behavior of the concrete. Lu and Li [39] concluded from their study that micro-crack inertia is one of the mechanisms responsible for the strain-rate sensitivity of the tensile strength of concrete-like materials and that the observed increase of tensile strength with strain rate from dynamic tensile tests can be largely attributed to the inertia effects of micro-cracks.

In general, when subjected to impact loads, the body is under dynamic equilibrium and the applied load and reactions are essentially not equal due to the presence of inertial component. The applied load is partly balanced by the inertial forces and partly by transmitted reactions. Up to a certain strain rate, the inertial component is insignificant and both applied load and reactions are more or less same, though both of them are higher than the corresponding values at static loading rates. This is termed as ‘rate sensitivity’ and is totally attributed only to material behavior. Once that critical strain rate is crossed and inertial forces become significant, the applied load becomes significantly higher than the reaction. The relative magnitude of applied load with respect to the reactions keeps on increasing with increased loading rate. This is termed as ‘influence of inertia’ and cannot be attributed to the material resistance. Obviously, inertia is dependent on size and shape of the specimen/component. This suggests that the measured applied load during impact does not provide the true material strength but inherently has an inertial component and thus it can be referred to as ‘apparent strength’. Inertia in dynamics is always present, even if the material behavior is linear elastic. However, it is important to note that in quasi-brittle materials, which undergo damage and softening, inertia is activated also because of the material softening and change of the failure mode. This is especially true in case of high strain rates, for both, dominant compression and tension.

This work aims at clearly bringing out the difference in true and apparent tensile strength of concrete subjected to high loading rates and to understand and find out the reason for this difference. In the paper, after discussing typical test methods for measuring material strength at high strain rates, the rate sensitive microplane model, which is used in the subsequent numerical simulations, is briefly discussed. The possible effect of inertia is demonstrated through consideration of dynamic equilibrium on a simple example. This consideration is also confirmed by numerical examples in which static and dynamic analyses of a simple elastic-cohesive FE model is subjected to direct tension. Three different sizes of elements are loaded at varying loading rates. The band of numerical results for tensile strength is compared with that of the experimental results available in literature. Finally, in order to investigate the validity of interpretation of measured dynamic tensile strength and fracture energy in the experiments, 3D finite element simulation of recently performed experiments on the so called modified split Hopkinson bar [8,41] is carried out for different loading rates and for two different materials, quasi-brittle (concrete) and brittle. The results are evaluated, compared with the experimental results and the corresponding conclusions are drawn out.

2. Indirect tension tests on concrete specimens

Hopkinson [42] experimentally tested behavior of various materials at high strain rates. On a long bar he generated compressive pulse by explosive charge or impacting bullet. At the end of the bar