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# Dynamic fracture of notched plain concrete beams: 3D finite element study

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Notched plain concrete beams loaded by impact hammer are numerically studied. The numerical and experimental results are compared in terms of load-deflection response, rate dependent tensile strength and rate dependent fracture energy. Moreover, the effect of impact velocity on reaction, strain rate, crack opening rate and crack velocity is predicted numerically and compared with the experimental results. The numerical model realistically captures the experimentally observed behavior of the notched plain concrete beams under dynamic loads. It is pointed out that to evaluate the true rate dependent material properties, such as tensile strength and fracture energy, inertia have to be filtered out otherwise for higher strain rates the material properties are significantly overestimated.

## 1. Introduction

The resistance and the failure mode of concrete structures/specimens are known to be significantly influenced by the loading rate [1,2]. There are principally three different effects, which have to be accounted for [3]: (1) the rate dependency of the growing micro-cracks (influence of inertia at the micro-crack level), (2) the viscous behavior of the bulk material between the cracks (creep of concrete or viscosity due to the water content) and (3) the influence of inertia, 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 while the third effect should be automatically accounted for through dynamic analysis where the constitutive law interacts with inertia.

It is important for the correct prediction of the resistance and failure modes that the contribution of inertia is considered explicitly through dynamic analysis and not through the adjustments in the constitutive law. At the same time, the constitutive law must interact correctly with the dynamic analysis. 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 influence of inertia dominates, however, the rate dependency cannot be neglected. Further detailed discussion can be referred to from Ožbolt et al. [3]. However, it should be pointed out that there are different aspects of inertia that need to be considered. For instance, (i) structural inertia forces, which are present even in case of elastic analysis; (ii) inertia forces activated due to the material softening (e.g. lateral compressive forces in uniaxial compression tests); or (iii) inertia at the crack tip that is responsible for crack branching.

The experimental evidence shows that concrete exhibits the strongest influence of loading rate under tensile load [1], though there is a significant influence of the loading rate on compressive strength as well [2]. To experimentally study the uniaxial tensile behavior of concrete is difficult even under quasi static load and therefore indirect methods such as Brazilian test, compact tension test etc. are often employed. It is however difficult to evaluate the direct dynamic uniaxial tensile behavior of concrete since the failure always occurs locally, near the loading points. Therefore, under dynamic load, the problem is studied through indirect tests such as Split Hopkinson bar (SHB) tests [4–13] or drop hammer tests [14–18]. The evaluation of experimental results of SHB tests based on the principle of uniaxial elastic wave propagation, under the

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assumption that concrete before cracking is linear elastic, shows that after reaching a certain critical strain rate tensile resistance progressively increases with increasing strain rate. Recently, it is demonstrated by Ožbolt et al. [3] that the main reason for the progressive increase of tensile resistance in SHB experiments is the fact that the experimental results are evaluated based on the assumption that before localization of macro crack concrete is linear elastic. It is argued that this assumption for concrete is not realistic, since even before localization of macro crack, the entire concrete specimen is already significantly damaged. Therefore, to evaluate experimental measurements objectively, damage should be somehow accounted for. The assumption of elastic behavior prior to fracture is valid only for elasto-brittle material (e.g. glass) [3]. It is emphasized that if damage is ignored, the effect of damage induced inertia is not filtered out from the results of experimental measurements and apparent instead of true strength of concrete is measured.

Using advanced numerical techniques it was recently demonstrated that the progressively increasing resistance of structural elements relying on tensile strength of concrete, such as direct tension [19], pull-out of anchor bolt from concrete block [20] and compact tension specimen [21], is related primarily to inertia effects. If in the analysis of these problems only rate sensitive constitutive law is used but inertia is not activated (rate sensitive static analysis), then no steep progressive increase in resistance was observed, which confirms that such increase is due to inertia. Furthermore, if the inertial effects are ignored, the failure mode remains independent of the loading rate, which is unrealistic. For the model to be realistic, it should be able to correctly account for the interaction between inertia and constitutive law in order to account for phenomena such as crack branching or change of failure mode due to the increase of loading rate. Standard macroscopic plasticity or damage based models have a limitation to predict, for instance, crack branching phenomena without additional energy criteria. Such models can not automatically account for the progressive increase of resistance, and therefore the progressive increase must be included as a part of the constitutive law itself. Consequently, the resistance may be correctly predicted, however, the failure mode and crack pattern might be incorrect.

In material science, drop hammer experiments are frequently used to study the behavior of concrete under impact load. Relatively recently, experiments on pre-notched concrete beams were performed by Zhang et al. [16,17] using hydraulic and drop hammer test machines. Based on the results of these experiments the fracture energy under dynamic load was attempted to be evaluated. The results of evaluation of the tests showed again a sudden rise in the fracture energy as a function of loading rate beyond a certain critical value of loading rate. Similar observations were made for reaction (resistance) as a function of loading rate. It is however, important to clarify and to understand the reasons for such sudden jumps in the fracture energy and resistance, which are considered as inherent material properties.

Zhang et al. [16,17] performed tests on notched beams under three point bending. The impact velocity was varied from low (order of $10^{-4}$ mm/s) to medium (order of 10 mm/s) and to high (order of 1000 mm/s). The tests from low to medium loading rates were performed using hydraulic testing machine and the fracture energy was evaluated following the procedure recommended by Elices, Guinea and Planas [22–25], using the following expression [16]:

$$G_F = \frac{W_{\exp} + W_{um}}{B(D-a)} \tag{1}$$

where, $W_{\exp}$ is the area under the experimental load-displacement curve, $W_{um}$ is the unmeasured energy due to the unbroken portion of ligament at the end of test, $B$ is the width of specimen, $D$ is the depth of the specimen and $a$ is the notch depth.

For the tests performed under high loading rates (impact velocities), a drop hammer test machine was utilized [16,17]. It was reported that under dynamic loading, there is neither a standard nor any generally accepted procedure for measuring fracture energy. The authors evaluated fracture energy based on the area under the reaction forces–displacement curve [16]. Such procedure is applicable for evaluating fracture energy from tests performed under quasi-static loading condition. However, it needs to be understood whether such evaluation of fracture energy is also valid for dynamic loading, since at higher loading rates (impact) structural inertia significantly contributes to reaction forces, even if the material is linear elastic. For correct estimation of the dynamic fracture energy, the structural inertia must be filtered out because fracture energy is a material and not structural property.

Experimentally it is difficult to separate the inertial component from the fracture energy evaluated as area under reaction-displacement curve. Therefore, to bring more light into the problem the experiments performed by Zhang et al. [16,17] are numerically replicated. Well established numerical procedure based on rate sensitive microplane model [26] and transient finite element (FE) dynamic analysis was utilized in the study. The numerical procedure has been validated over a large number of problems on concrete fracture [20,27–31]. First, to validate the numerical results, they are compared with experimental results reported in Refs. [16,17]. Subsequently the fracture energy is evaluated as suggested by Zhang et al. [16], i.e. by dividing the area under the reactions versus vertical displacement curve by the cross section area in the region above the notch. Further, for better understanding of the structural effects on fracture energy, the evaluation of fracture energy is performed by considering the stress-strain response of the single finite element in the zone of cracking, i.e. just above the notch. The results are evaluated and discussed in detail to understand the correct evaluation procedure for fracture energy under dynamic loading. Similar exercise is also performed for evaluation of tensile strength. Finally, the main objective of the study is to demonstrate that the used computational approach is able to correctly replicate the structural response of notched plain concrete beams under impact loading and to demonstrate that for the investigated strain rates (up to approximately 30/s) the rate dependent true resistance of concrete material is approximately linear in semi-log scale.

## 2. Three-dimensional dynamic rate dependent FE analysis

### 2.1. Constitutive law – rate sensitive microplane model for concrete

In the microplane model the material response is computed based on the monitoring of stresses and strains in different predefined directions. Integrating microplane stresses in a thermodynamically consistent way it is possible to calculate macroscopic stress tensor. In the model material is characterized by the uni-axial relations between stress and strain components on planes of various orientations. Each microplane is defined by its unit normal vector $n_i$ (Fig. 1). Microplane strains are assumed to be the projections of macroscopic strain tensor $\varepsilon_{ij}$ (kinematic constraint). On the microplane are considered normal ($\sigma_N$, $\varepsilon_N$) and two shear stress-strain components ($\sigma_M$, $\sigma_K$, $\varepsilon_M$, $\varepsilon_K$). To realistically model concrete, the normal microplane stress and strain components have to be decomposed into volumetric and deviatoric parts ($\sigma_N = \sigma_V + \sigma_D$, $\varepsilon_N = \varepsilon_V + \varepsilon_D$). Unlike to most microplane formulations for concrete, which are based on the kinematic constrain approach, to prevent unrealistic model response for dominant tensile load (strong localization of strains), kinematic constrain is relaxed [26]. Based on