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Influence of high loading rates on behavior of reinforced concrete beams with different aspect ratios – A numerical study

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A R T I C L E I N F O

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A B S T R A C T

The failure mode of the reinforced concrete (RC) beams having varying aspect ratios (ratio of shear span to depth) is known to vary from predominantly shear to predominantly flexure with the increase in aspect ratio. It is further known that there is a significant influence of loading rate on the resistance and the failure mode of the beams, namely the failure mode of a beam failing by flexure under static loads changes to shear failure when subjected to high loading rate. In this work, numerical investigations are carried out on cantilever RC beams having different aspect ratios under high loading rates. First, the failure modes of the beams are obtained under static loading and the same is compared with the well-accepted results in literature. The numerical modeling technique already proven by the authors on various problems is then utilized to predict the failure modes of the beams when they are subjected to higher loading rates. It has been shown that the influence of loading rate is much more prominent on beams with larger aspect ratios compared to the beams with smaller aspect ratios. The failure mode of beams with large aspect ratios tends to change from flexure to shear with increasing loading rate. For beams with small aspect ratios, the failure mode is relatively unaffected by the loading rate. The increase in resistance due to loading rate for beams with different aspect ratios is also evaluated and reported.

1. Introduction

It is well known that high loading rates significantly influence the behavior of reinforced concrete structural elements that primarily consist of increase in resistance and change in failure mode of the structural members [1,2]. Typically, high loading is considered to change the mode-I fracture (under static loading) to a mixed-mode fracture (under dynamic loading). This can be visualized practically as a beam failing essentially in flexural mode, due to quasi static loads, failing in a shear mode under high rate loads [1]. Such an influence is attributed to various factors such as, influence of strain-rate on strength, stiffness, ductility and to the activation of inertia forces. Under dynamic loading, the response of structures is governed by three different effects [1,2]: (1) the rate dependency of the growing microcracks, (2) the viscous behavior of the bulk material between the cracks, and (3) the influence of structural inertia forces. In numerical modeling, 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 structural inertia forces [1,2]. Depending on the material type and the loading rate, the first, second or third effect may dominate. It has been shown by several examples on dynamic fracture of concrete that, in case of concrete, the first two effects are important for relatively low and medium strain rates, while for higher strain rates (impact) the last effect dominates [2–4], although the effect of strain rate cannot be neglected.

Further, it is well-accepted that the aspect ratio of a structural member, defined as the ratio of shear span, '*a*', to the depth, '*d*', of the member (beam or column) is related to the probable failure mode of the structural member [5,6]. The failure mode is reported to change from flexure failure to diagonal tension failure to shear failure to compression failure as the 'a/d' ratio changes from relatively high value of more than 6 to less than 1 [5,6]. Recently, Perdomo et al. [7] reported the experimental results as well as mathematical modeling of fracture of RC elements with different aspect ratios. According to them, modeling of RC structural elements with arbitrary aspect ratios is one of the most difficult aspects in modeling the fracture of RC elements; however, it is a fundamental issue [7]. They reported on the basis of experimental and numerical studies that for beams and columns of large aspect ratios the most important effect is bending but with its reduction, shear stresses become progressively more important and may be the dominant failure mechanism [7].

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It is therefore interesting and important from design perspective, to investigate the behavior of RC beams of different aspect ratios under dynamic loading. Currently, as per authors' knowledge no such tests are available in the literature. It is generally difficult, time consuming and economically demanding to perform such tests covering a range of aspect ratios and loading rates. On the other hand, numerically the problem can be solved relatively easily, provided the numerical model is able to capture the dynamic behavior of RC beams realistically. In this paper, it is attempted to address the issue of the influence of high loading rate on the failure mechanism and resistance of structural elements with different aspect ratios. A reinforced concrete cantilever beam with four different aspect ratios from 2 to 8 is numerically tested under a range of loading rates. The reinforcement details of the beam are kept the same for all the aspect ratios. First, the beams of four different ratios are analyzed under static loads and the known influence of the aspect ratio under static loading is confirmed. Then the beams with different aspect ratios are subjected to different levels of high rate loading to understand the influence of loading rate in each case.

Microplane model with relaxed kinematic constraint [8] has been followed as the constitutive law for concrete, while the rate dependency is considered as per the model by Bažant et al. [9,10]. The formulations followed in this work have been previously validated against several examples and is known to predict the static as well as dynamic behavior of RC structural elements with high confidence [1,11,12].

2. Details of specimen and numerical test matrix

In this work, a rectangular reinforced concrete cantilever beam is investigated. The cross-sectional details of all the beams are kept the same and the length of the beam (from loading point to fixed end) is varied to vary the aspect ratio. Fig. 1 shows the details of the beams numerically analyzed. Four different lengths (L) of the beams were considered for this study namely 800 mm, 1600 mm, 2400 mm and 3200 mm. Therefore the aspect ratios, defined as the ratio of length L to total depth, of 2, 4, 6 and 8 were considered.

Concrete properties were considered in the range of normal strength concrete. The yield and ultimate stress values for reinforcing steel were taken as the likely mean values that can be expected for high yield strength deformed bars with a characteristic yield strength of 415 MPa. The actual material properties for the beam used in the analyses are: Compressive cylinder strength of concrete, $f'_c = 40.0$ MPa; Elastic modulus of concrete, E_c = 30,000 MPa; Poisson's ratio for concrete, ν_c = 0.18; Tensile strength of concrete, f_t = 3.50 MPa; Fracture energy, G_F = 0.09 N/mm; Concrete mass density ρ_c = 2400 kg/m^3; Reinforcement yield stress, f_y = 480 MPa; Reinforcement ultimate stress, f_u = 550 MPa; Elastic modulus for reinforcement, E_s = 200,000 MPa; Poisson's ratio for reinforcement, ν_s = 0.33; Steel mass density ρ_s = 7850 kg/m^3.

First, all the beams were analyzed under quasi-static loading to verify the accepted failure mechanisms for beams of different aspect ratios under normal loading. The loading rates were defined in terms of drift ratio, δ_r, per unit time. For beams deflecting predominantly in bending, the drift ratio (also known as chord rotation) is almost proportionally related to the strains in the beam and is defined as the displacement at loaded end, Δ, divided by the length of the beam, L:

$$\delta_r = \Delta/L \quad (1)$$

However, it may be noted that the same drift rate may not correspond to the same strain rate in beams with different aspect ratios due to the difference in their deflection profiles and change of failure mode.

The basic drift rate was considered as $\delta_{r,b}$ = 0.015625/s. The analyses were performed for all the cases with drift ratios as 2, 4, 6 and 8 times this basic drift rate. For beam with aspect ratio = 8, the basic drift rates corresponded to a displacement rate of 50 mm/s, while the other rates corresponded to displacement rates of 100 mm/s, 200 mm/s, 300 mm/s and 400 mm/s respectively.

The beam longitudinal reinforcement was assumed to have sufficiently large anchorage length inside the support so that bond failure would not occur in any case. This allowed for using perfect connectivity between concrete and reinforcement nodes to be used while numerically modeling the beam.

3. Numerical modeling of beams

The numerical modeling of the beams was performed within the framework of 3D Finite element analyses. In order to obtain reliable results from such analysis, it is important to validate the results with experimental results. The numerical modeling philosophy followed in this work has been validated against several experiments under static and high rate loading [1,12–15]. The numerical modeling procedure is briefly described below.

3.1. Constitutive law – rate dependent microplane model for concrete

In the microplane model, the material response is calculated based on the monitoring of stresses and strains in different predefined directions. Integrating microplane stresses in a thermodynamically consistent way, from a known macroscopic strain tensor it is possible to calculate macroscopic stress tensor. The constitutive framework is similar to discrete type of the models (e.g. random particle model) with the difference that the model is formulated in the framework of continuum [8]. In this model, material is characterized by the relation between stress and strain components on planes of various orientations. The used microplane model [8] is based on the so-called relaxed kinematic constraint concept. It is a modification of the M2 microplane model proposed by Bažant and Prat [16].

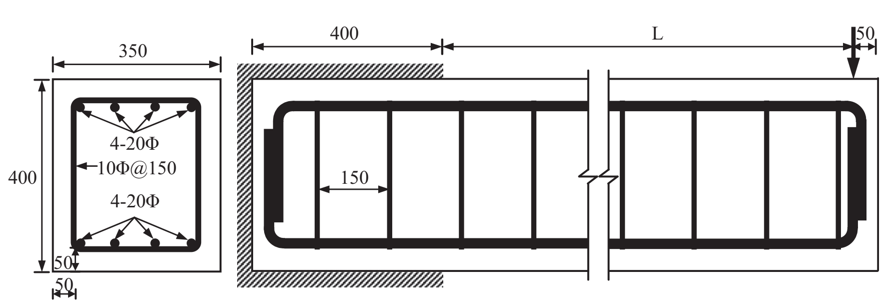

Fig. 1. Details of RC beam investigated.