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Effect of dynamic loading on concrete properties

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Abstract

Concrete is very strain rate sensitive material, especially in tension. In this work the effect of dynamic loading on concrete properties in terms of rate dependent failure mode, resistance, tensile strength and fracture energy will be presented. Through own experiments and numerical modeling of L-specimen it is shown that inertia effects are responsible for progressive increase of resistance and rate dependent failure mode. Numerical results and their comparison with experiments show that the true fracture energy and tensile strength increases approximately linear in semi-log scale with strain rate and that approximately follow rate dependent constitutive law used in the computation.

Key words: concrete, dynamic loading, L-specimen, experiments, numerical modeling, tensile strength, fracture energy, failure patterns

Utjecaj dinamičkog opterećenja na svojstva betona

Sažetak

Beton je materijal iznimno osjetljiv na brzinu deformacije, posebice kada je izložen vlaku. U ovom radu će se prikazati utjecaj dinamičkog opterećenja na svojstva betona ovisnih o brzini kao što su oblik sloma, nosivost, vlačna čvrstoća i energija loma. Primjenom vlastitih eksperimenata i numeričkog modeliranja betonskog uzorka L-oblika pokazano je da su za progresivni rast nosivosti i način sloma uzorka odgovorni inercijalni efekti. Numerički rezultati i njihova usporedba s eksperimentima pokazuju da prava energija loma i prava vlačna čvrstoća s porastom brzine deformacije rastu približno linearno u polu-logaritamskom mjerilu te da slijede konstitutivni zakon ovisan o brzini deformiranja koji je korišten u numeričkoj analizi.

Ključne riječi: beton, dinamičko opterećenje, uzorak L-oblika, eksperimenti, numeričko modeliranje, vlačna čvrstoća, energija loma, oblik sloma

1. Introduction

Concrete is the most widely used construction material in the world due to its numerous advantages such as strength, stiffness, durability, dimensional stability and economic efficiency. Hence, it is important to realize that concrete structures are more often expose to various types of dynamic loads rather than static loads. The behaviour of concrete structures under dynamic loads is complex due to significant sensitivity of concrete to strain (loading) rate. The rate dependent response of concrete can be explained by three different effects [1]: (1) through the viscous behaviour of the bulk material between the cracks (creep of concrete or viscosity due to the water content), (2) through the rate dependency or rate sensitivity of the growing micro-cracks (influence of inertia at the micro-crack level) and (3) through the influence of inertia effects, which can significantly change the state of stresses and strains of the material. The first effect is important for relatively low loading rates and the last two effects dominate for medium and high loading rates (e.g. dynamic loading). Thus, under high loading rate two different mechanisms influence the structural behavior. First is the strain rate influence on strength, stiffness and ductility, and second, the inertia effects activated, which influence the resistance and failure mode of concrete structure. In numerical modeling, the first two effects can be accounted for by the constitutive law. The third effect should be automatically accounted for through dynamic analysis, where the constitutive law interacts with structural inertia [1-5].

The experimental evidence shows that concrete exhibits the strongest influence of loading rate under tensile load [6]. Since concrete is inherently weak in tension, the response of concrete under tensile loading is key to understanding and using concrete in structural elements. To experimentally study uniaxial tensile behavior of concrete is difficult, therefore, various testing techniques and specimen types, for instance drop hammer test [7], splitting test etc. [8], as well as different measurement methods have been used. These studies usually investigate the differences between tensile strength and fracture energy under static and dynamic loading and suggest some simple relations to predict behaviour of concrete under high loading rates. Principally, experiments show that apparent strength and fracture energy increase with increase of strain (loading) rate and that for strain rates larger than approximately 10/s both increase progressively with increase of strain (loading) rate (Figure 1, DIF is defined as the ratio between dynamic and corresponding quasi-static value). To this end, there is no clear consensus on the reason for this progressive increase of dynamic strength and fracture energy under high loading rates, hence, it is generally argued on the fundamental cause of progressive increase. Due to the complexity arising from the composite nature of the concrete material, behaviour of concrete structures under dynamic loading is very difficult to understand only from experiments. Hence, in order to overcome the limitations of experimental tests, numerical methods can be helpful.

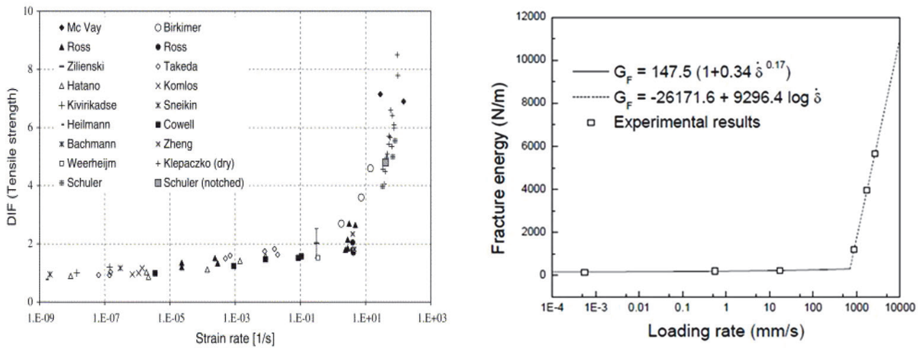

Figure 1. a) Dynamic increase factor (DIF) for tensile strength as a function of strain rate - test data ([9]) and b) rate dependent fracture energy ([7])

On the other hand, numerically the problem can be solved relatively easily if the numerical model is able to capture the dynamic fracture behavior realistically. The main advantage of numerical modeling is that the influence of individual parameters can be studied separately and in more detail. This provides better understanding of the concrete properties, e.g. tensile strength and fracture energy, and influence of inertia on the same. Therefore, numerical analysis has become increasingly important in understanding concrete behaviour under dynamic loading. Many researchers have proposed various numerical models to predict response of concrete under dynamic loading. However, only very limited studies aimed at understanding the complete fracture of concrete and influence of dynamic loading on the failure mode, see for example [3]. Hence, numerical modeling of concrete fracture under dynamic loading is still a challenging topic. Considering results from a large amount of experimental data under different loading (strain) rates, the dynamic increase factor (DIF) of concrete strength and fracture energy is analytically determined and explicitly accounted for as a part of the various different constitutive laws used in standard computational codes. In such way, structural response depends on the used constitutive model. In addition, such material models are capable of giving correct prediction on structural resistance and load carrying capacity, namely apparent strength, while realistic information on change in failure mode and crack pattern of a structure and/or its structural elements cannot be captured. Principally, high loading tends to change failure mode from mode-I to a mix-mode failure (Figure 2) [10]. The main reason are structural inertia forces at the crack tip which prevents mode-I propagation and force crack to split (branch) into two new cracks. Hence, for a model to be realistic, it should be able to correctly account for the

interaction between inertia effect and constitutive law, and it should realistically capture phenomena such as crack branching or change of failure mode due to the increase of loading rate ([3]). Only such FE model is able to predict concrete behaviour under a wide range of loading rates for a variety of different loading rates.
Since experimental and numerical fracture studies exists manly for mode-I fracture, complete study of fracture behavior of concrete will be presented through analysis of L-shaped specimen. L-shaped specimen poses a very interesting problem from the point of view of dynamic fracture of concrete [2,5]. Both static and dynamic experimental and numerical 3D FE analysis will be shown to identify the influence of loading rate on the rate dependent failure mode and material properties, namely tensile strength and fracture energy. While the idea of influence of loading rate on tensile strength and fracture energy of concrete is not a new one, it requires new understanding. Therefore, in order to enhance understanding of the dynamic fracture of concrete, the question that naturally arises is should the observed dynamic increase factor of tensile strength and fracture energy of concrete be attributed as inherent material property (i.e. it can be attributed to only the strain rate effect) or rather to structural effect due to inertia? Based on the results evaluated from experiment and numerical analysis the main conclusions will be presented.

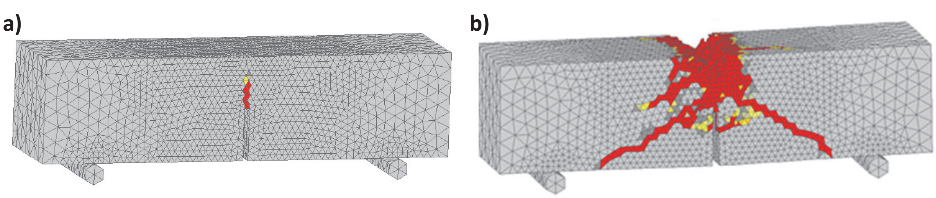

Figure 2. Failure mode a) mode-I (at impact velocity of 2.64 m/s), b) mix-mode (at impact velocity of 50 m/s) [10]

2. L-shaped concrete specimen

The L-shaped specimen is often used as benchmark test for the validation of numerical models for cracking of concrete under static loading [11]. Ožbolt et al. [2] numerically studied the influence of displacement rate on the crack propagation of L-specimen. It is reported that structural inertia forces are responsible for the change in crack propagation, i.e. the crack propagation is changing from horizontal direction (under static loading) to a vertical (under dynamic loading). Recently, comprehensive experimental and numerical study of dynamic fracture of L-shaped concrete specimen was presented and discussed [12]. Hence, in the present paper summary of results is given.

2.1. Experimental study

The dimensions of the tested specimen and test-set up are shown in Figure 3. The specimen was fixed with steel plates rigidly bolted to the supporting plate. The average material properties of tested concrete mixtures are summarized in Table 1. Loading on the specimen was provided by means of machine actuator (loading piston) in upward direction (see Figure 3). The displacement rate measured on the tested specimens ranged from 0.25 mm/s (quasi-static loading) up to 2400 mm/s. A more detailed description of material properties, specimen geometry, test setup and measuring instrumentation are presented in [12].

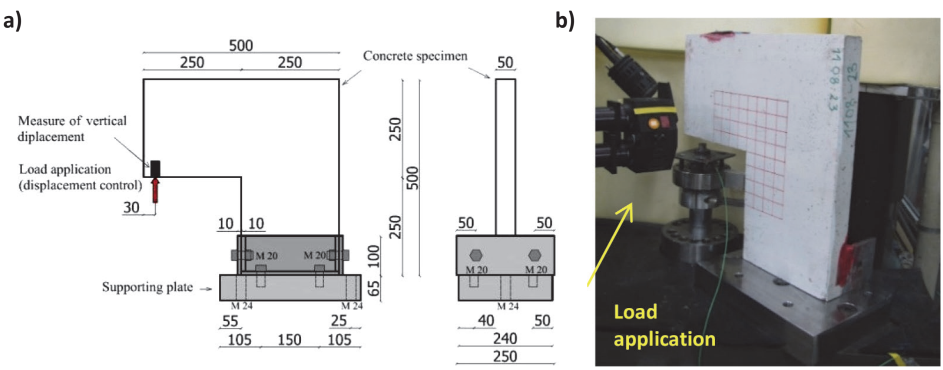

Figure 3. Geometry and test setup of L-specimen

Table 1. Average mechanical properties of experimental concrete mixtures

Batch	Density ρ_c [kg/m^3]	Tensile splitting strength $f_{t,sp}$ [MPa]	Compressive strength f_c [MPa]
1	2205	3.5	51.4
2	2214	3.5	56.4

A total of 12 experimental results obtained from performed tests are analyzed. Figure 4 shows the plot of measured peak load as a function of the displacement rate in semi-logarithmic scale. From experimental results it is clear that peak load is rate dependent. The peak load varies from approximately 4 kN for quasi-static loading to 130 kN for displacement rate of 2400 mm/s. Hence, for relatively low displacement rates the peak load increases proportionally with increase of displacement rate and for higher displacement rates, higher than 100 mm/s, the peak load increases progressively.

In Figure 5 are shown typical crack patterns observed for different displacement rates. It can be noted there is a significant difference in the failure patterns and crack propagation between the low and higher displacement rates. In general, there is a tendency that with the increase of loading rates the failure mode changes from horizontal to vertical, i.e. for relatively low loading rates there is only one crack that is approximately perpendicular to the loading direction, however, with increase of displacement rate the crack becomes more inclined with respect to the loading direction. Furthermore, in most cases with higher displacement rates crack branching with numerous small cracks were observed. Such a phenomenon was also reported in [3] with the compact tension specimen exposed to high loading rates

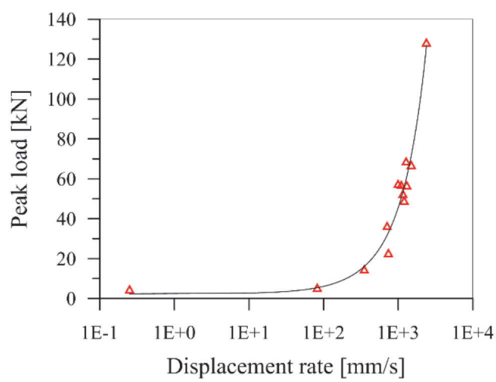

Figure 4. Peak load measured for different displacement rates

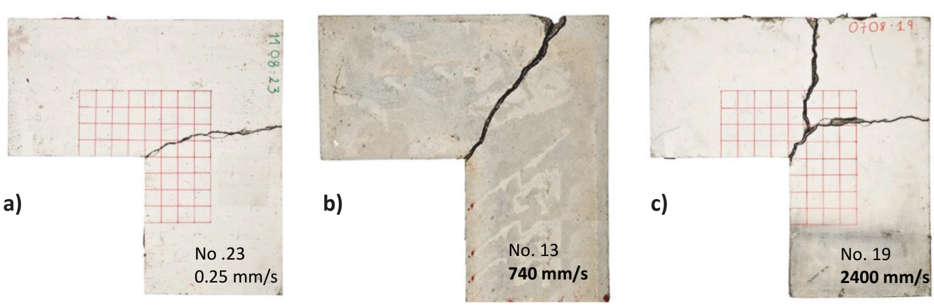

Figure 5. Typical crack patterns for different displacement rates

2.2. Numerical study

In order to overcome limitations of experiments and to gain a better understanding on the structural response above mentioned tests are also simulated numerically. The comparison of numerical results against experiment is performed in terms of rate dependent peak load, tensile strength, fracture energy and the failure mode. The geometry, boundary conditions and loading are same as in the experiments. The overview of concrete properties used in the finite element study are summarized in Table 2. In the present numerical model rate dependency is accounted for through the rate dependent microplane model for concrete [13], while explicit dynamic analysis is performed to account for the influence of inertia (more details see [14]). In static and dynamic analysis standard four node solid elements are used (see Figure 6). To obtain results objective with respect to the element size, crack band approach is employed as a regularization method (smeared crack approach) [15].

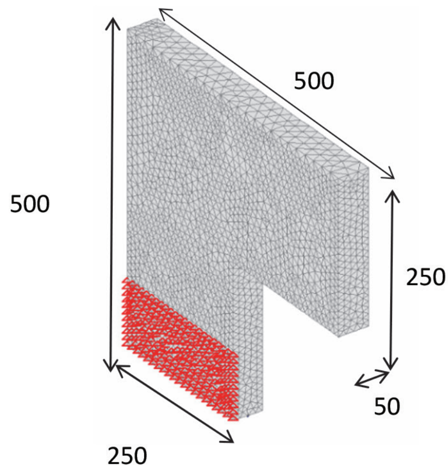

Figure 6. 3D FE model and boundary conditions

Table 2. Overview of the material properties used in numerical analysis

Young's modulus, E_c [GPa]	32.2
Poisson's ratio (assumed value), ν_c	0.18
Mass density, ρ_c [kg/m^3]	2210
Tensile strength, f_t [MPa]	3.12
Compressive strength, f_c [MPa]	46.25
Fracture energy, G_F [J/m^2]	58.56

Figure 7 shows comparison between crack patterns obtained from the FE analysis and experiments for different displacement rates. Note that the crack (dark zone) is indicated in terms of maximum principal strains that are larger than critical strain $\varepsilon_{cr}= w_{cr}/h$ that corresponds to critical crack opening. The critical crack opening w_{cr} is assumed to be 0.1 mm and h is the average element size (smeared crack approach). Obviously, results of numerical simulations are consistent with the results obtained from the experiment. For quasi-static and relative low loading rates there is only one crack which is nearly horizontal, perpendicular to the loading direction, however, with increase of loading rate the crack becomes more inclined, parallel to the loading direction. As the loading rate increases, the direction of the critical principal tensile stresses change due to the presence of inertia, see [3]. As can be seen from Figure 7, in case with highest loading rate there is also crack branching observed.

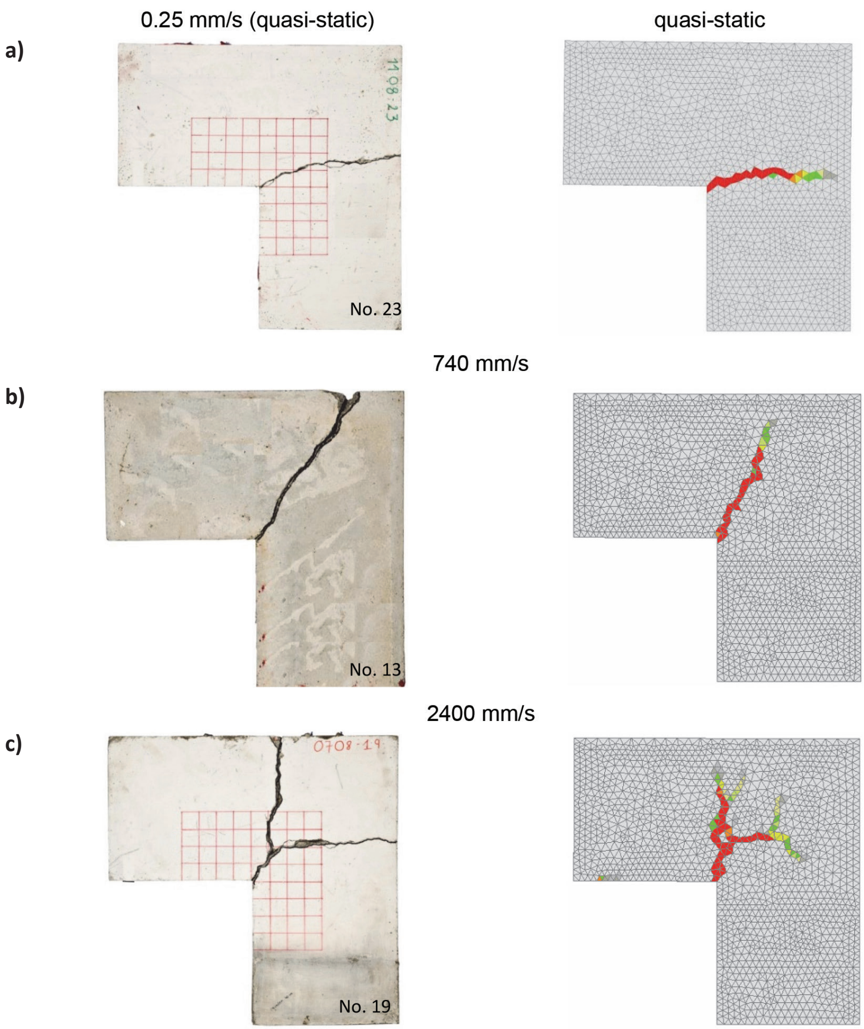

Figure 7. Experimentally (left) and numerically (right) observed crack patterns for different loading rates

Comparison of measured values of peak load with computed one as a function of applied loading (displacement) rate is shown graphically in Figure 8a), in semi-logarithmic plot. The trend in both cases shows that the peak load increases with the increase of displacement rate, as expected. This increase becomes more pronounced when the displacement rate is greater than 100 mm/s while for displacement rates higher of approximately 1000 mm/s this increase is progressive. It is important to note that increase coincides with moment when crack propagation is changing direction from horizontal and tends to become vertical. Finally, progressive increase of peak load is observed when the crack propagates almost vertical.

In order to provide more insight on the structural inertia effects the evaluation of tensile strength is performed by considering the stress-strain response of a single finite element at the onset of cracking. Hence, Figure 8b) shows DIF for peak loads (DIF is defined as the ratio between dynamic and corresponding quasi-static value) measured in the analysis and experiment as a function of strain rate and DIF for tensile strength of concrete. Up to the strain rate of approximately 10/s there is linear increase in DIF for peak load which nicely follow the rate dependent constitutive law for tensile strength. On the contrary, for strain rates of approximately 10/s and higher there is significant increase of peak load. Since the rate dependent constitutive law is approximately linear in semi-logarithmic scale, these suggest that the progressive increase of load is related to inertial effects activated due to cracking of concrete.

Numerically obtained DIF for true tensile strength and fracture energy evaluated from a single finite element as a function of strain rate are shown in Figure 9 (plotted in semi-log scale). As can be seen, there is no progressive increase of the true strength and true fracture energy with increase of strain rate [13]. This was expected since this response is coming out from constitutive law without the contribution of inertia [13].

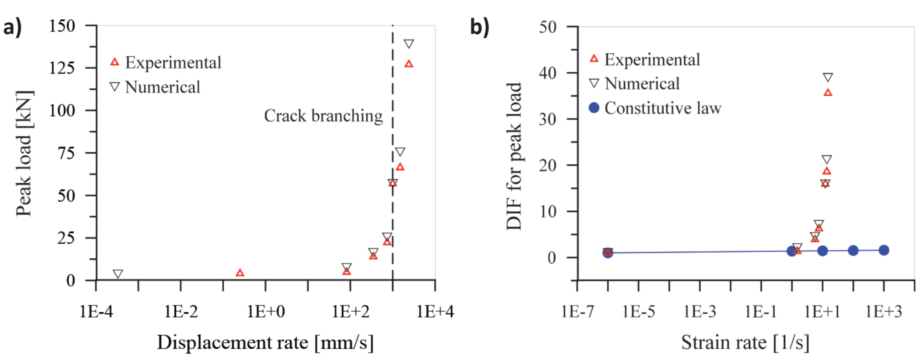

Figure 8. Comparison between numerical and experimental results for a) peak load at different loading rates b) DIF for peak load as a function of strain rate and DIF for tensile strength

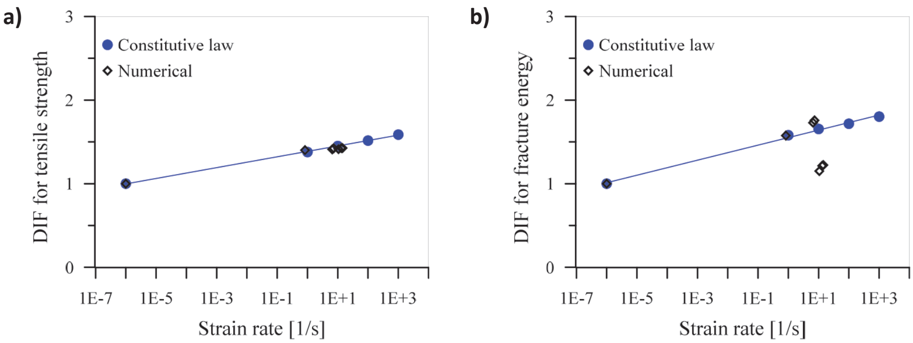

Figure 9. Numerically obtained DIF a) on tensile strength and (b) fracture energy as a function of strain rate

3. Conclusion and recommendations

In the present paper the influence of dynamic loading on the concrete properties through numerical and experimental study of the L-specimen is presented. Both, experiments and numerical analysis show that loading rate significantly influences the failure mode of the L-specimen. Numerically obtained crack patterns correspond very well with the experimentally observed. Hence, it is shown that relatively simple modeling approach based on continuum mechanics, rate dependent microplane model and standard finite elements is capable to realistically replicate complex phenomena related to dynamic fracture of L-specimen. As expected, experiments and numerical analysis show that peak load increases with increase of loading (strain) rate. Moreover, for loading rates higher of approximately 10/s there is progressive increase of load that is controlled mainly by structural inertia. The evolution of numerical results shows that tensile strength and fracture energy exhibit no progressive increase for high loading rates but follows approximately the rate dependent constitutive law used in the computation. Overall, it can be concluded that for higher strain rates, larger than approximately 10/s, inertial effects dominate and cause progressive increase of load, change of failure mode and crack branching. Hence, for correct estimation of 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.

References

1. Ožbolt J, Sharma A, Reinhardt HW. Dynamic fracture of concrete – compact tension specimen. Int J Solids Struct 2011;48(10):1534–43.

2. Ožbolt J, Sharma A. Numerical simulation of dynamic fracture of concrete through uniaxial tension and L-specimen, Engineering Fracture Mechanics 2012;85: 88-102

3. Ožbolt J, Bošnjak J, Sola E. Dynamic fracture of concrete compact tension specimen: Experimental and numerical study. Int J Solids Struct 2013;50:4270-8.

4. Ožbolt J, Sharma A, Irhan B, Sola E. Tensile behavior of concrete under high loading rates. Int J Impact Eng 2014;69:55-68.

5. Ožbolt J, Bede N., Sharma A, Mayer U. Dynamic fracture of concrete L-specimen: Experimental and numerical study. Engt Frac Mech 2015;14:27-41.

6. Malvar LJ, Ross CA. Review of strain rate effects for concrete in tension. ACI Mater J 1998;95(6):735-9.

7. Zhang XX, Ruiz G, Yu RC, Tarifa M. Fracture behavior of high-strength concrete at a wide range of loading rates. Int J Impact Engng 2009;36:1204-9.

8. Weerheijm J, Van Doormaal JCAM. Tensile failure of concrete at high loading rates: new test data on strength and fracture energy from instrumented spalling tests. Int J Impact Engng 2007;34(3):609–26.

9. Schuler H, Mayrhofer C, Thoma K. Spall experiments for the measurement of the tensile strength and fracture energy of concrete at high strain rates. Int J Impact Eng 2006;32(10):1635–1650.

10. Bede N, Ožbolt J, Sharma A, Irhan B. Dynamic fracture of notched plain concrete beams: 3D finite element study. Int J Impact Engng 2015;77:176–88.

11. Winkler B, Hofstetter G, Niederwanger G. Experimental verification of a constitutive model for concrete cracking. Proc Inst Mech Engng, Part L. J Mater Des Appl 2001;215(2):75–86.

12. Bede N. Numerical and experimental study of concrete fracture under dynamic loading. PhD thesis. Croatia: Faculty of Civil Engineering, University of Rijeka; 2015.

13. Ožbolt J, Li Y, Kožar I. Microplane model for concrete with relaxed kinematic constraint. International Journal of Solids and Structures 2001;38:2683–711.

14. Irhan B. High velocity impact and fragmentation of concrete:Numerical simulation. PhD Thesis, University of Stuttgart, 2014.

15. Bažant ZP, Oh BH. Crack band theory for fracture of concrete. Mater Struct RILEM 1983;16(3):155–77.