ISSN 1996-3343

Asian Journal of Applied Sciences

Knowledgia
SCIENTIFIC
A Place to Publish Outstanding Research

http://knowledgiascientific.com

Asian Journal of Applied Sciences 3 (2): 145-152, 2010
ISSN 1996-3343

Stress-Strain Behavior of Normal Strength Concrete Subjected to High Strain Rate

A.S.M.Z. Hasan, R. Hamid, A.K. Ariffin and R. Gani
Department of Civil and Structural Engineering,
Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia,
43600 UKM Bangi, Selangor DarulEhsan, Malaysia

Abstract: Dynamic behavior of concrete specimen can be studied using experimental method such as Split Hopkinson Pressure Bar Test. This test is tedious to conduct and costly too. However, it can be simulated by using finite element method. This study investigated the dynamic behavior of concrete based on finite element method under high strain rate. The dynamic stress-strain behavior for cylindrical concrete specimen is studied with 36 mm diameter and 36 mm length under the strain rate of 350, 500 and 700 sec^{-1}, respectively. The results indicate that the peak stress of cylindrical concrete specimen increase with the increase of strain rate. The peak stresses are found 28.6, 39.9 and 76.3 MPa at ultimate strain of the values of 0.0055, 0.0077 and 0.011 under the stress rate 350, 500 and 700 sec^{-1}, respectively. The highest concentrations of stresses are found at the center of the concrete specimen under the stress rate 350 and 500 sec^{-1} whereas, the highest concentration of stress is observed at the outer surface of concrete under the stress rate 700 sec^{-1}. The comparative study shows that numerical results of present identification substantially agreed with the experimental results. Therefore, the numerical analysis can be widely used to identify the stress-strain behavior of concrete under the high strain rate. The significance of this study is to give the proper guideline for the selection of concrete model for stress-strain analysis of normal strength concrete under high strain rate.

Key words: Finite element, high strain rate, Split Hopkinson Pressure Bar (SHPB), stress-strain

INTRODUCTION

Concrete structures often face high rate dynamic loadings such as earthquake, impacts, explosions, etc. Therefore, it is necessary to know the behavior of concrete materials in order to predict the response of the concrete structure under such kind of loading. The mechanical properties of cement-based materials are sensitive to strain rate. The dynamic mechanical properties of concrete have great significance in the structural design. In the earlier study, Georgin and Reynouard (2003) had studied strength, hardness and ductility of concrete, their research results indicated that uniaxial compressive strength of concrete apparently increase with high rate of loading.

Corresponding Author: A.S.M.Z. Hasan, Department of Civil and Structural Engineering,
Faculty of Engineering and Built Environment,
Universiti Kebangsaan Malaysia, 43600 UKM Bangi,
Selangor DarulEhsan, Malaysia

In the past, several researches carried out experiments for the investigation of dynamic properties of concrete, among them Hentz *et al.* (2004) had studied two main properties of concrete; namely, viscoelasticity of harden cement and enlargement of crack. The property of viscosity depends on strain rate and free water in the materials of concrete (Rossi *et al.*, 1992). This study had showed that the rate effect of concrete is affected by two factors; the free water viscosity dominating under lower loading rate and the inertia effect under higher loading rate.

Previously, there were many attempts to ascertain the dynamic behavior of concrete using the experimental process. Most of the experiment have been carried out using the Split Hopkinson Pressure Bar (SHPB) test to generate high strain rate up to 10^3 sec^{-1} (Grote *et al.*, 2001; Riisgaard *et al.*, 2007) sometimes the shape of this device has been modified (Schuler and Hakan, 2006) to obtain accurate results. Indeed, this device is well established for the metallic materials to determine the dynamic behavior. The results obtained from this device are affected by the large number of factors such as difficulties in obtaining accurate measurement of stress-strain diagram, variation in signal processing along with the dispersion correction and safety factor. Due to these problems, alternatively, Finite Element (FE) analysis has been widely used to study the dynamic behavior of concrete under impact, blast or any other high dynamic loading (Krauthammer *et al.*, 2003; Donze *et al.*, 1999). This study is mainly concerned with the numerical simulation of Normal Strength Concrete (NSC) under high strain rate.

The main purpose of this study is to investigate the dynamic behavior particularly stress-strain behavior of NSC specimen by using software ABAQUS/Explicit (2007) version 6.7 under high strain rate. The verification of the accuracy of the obtained numerical results with the experimental results and finally, the present simulation with elastic model capability of concrete are analyzed and presented herein.

MATERIALS AND METHODS

Specimen and Simulation Arrangement of SHPB Test

Cylindrical specimen of 36 mm diameter and 36 mm length of NSC is simulated to investigate the dynamic behavior under the applied strain rate 350, 500 and 700 sec^{-1}. An elastic three dimensional model is formed in the year 2008, along with the combination of isotropic properties through out the simulation of concrete specimen. The simulation arrangement of SHPB test is shown in Fig. 1.

In the present study, concrete grade 30 (Ultimate compressive strength of concrete 30 MPa) according to Malaysian Standard is used to simulate and the concrete is assumed as homogenous materials. The material properties of concrete and SHPB used in this simulation are summarized in Table 1.

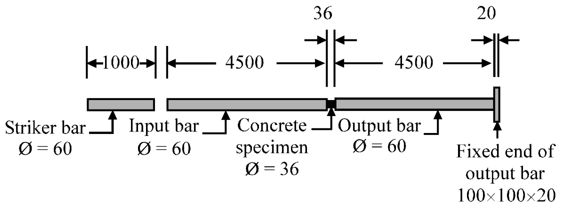

Fig. 1: Simulation arrangement of SHPB (dimension in mm)

Table 1: Material property of the components of SHPB test and concrete

Property	Parameters	Unit	Concrete	Steel
Elastic (isotropic)	Density (ρ)	kg m^{-3}	2500	7850
	Modulus Young (E)	GPa	30	200
	Poisson's ratio (v)	-	0.2	0.3

Contact Properties

A general contact algorithm is selected between cylindrical concrete specimen and input bar as well as output bar. Surface to surface contact properties are defined of the two contact surfaces for proper transmission of shear and normal forces across the interface. A mechanical interaction model, excluding friction loss is defined to model the connection between concrete specimen and input bar and concrete specimen and output bar. In ABAQUS/Explicit, hard contact is utilized to formulate the tangential and normal forces in the present model. The term explicit refers to the fact that the state at the end of the increment is based solely on the displacements, velocities and accelerations at the beginning of the increment. ABAQUS/Explicit (2007) allowed the modeling of material degradation and failure, avoiding convergence difficulties by explicitly advancing the kinematics state. The kinematics conditions at the beginning of one increment are used to calculate those at the beginning of the next increment. A central difference rule is used to integrate the equation of motion explicitly through time.

Load and Boundary Condition

The applied load of concrete specimen is likely to be an impact loading procedure. The following expression is used to calculate the dynamic loading (impact) of concrete:

$$\dot{\varepsilon}_s(t) = \frac{V_{bar}}{l_S} \tag{1}$$

where, $\dot{\varepsilon}_s(t)$ is strain rate, V_{bar} is bar velocity and l_s is specimen length.

For generating the strain rate 350, 500 and 700 sec^{-1}, the velocity of the striker bar to impact the input bar are kept 12.6, 18.0 and 25.2 m sec^{-1}, respectively which are calculated by using Eq. 1. The last end of output bar is kept fixed so that the load is allowed all three degree of freedom to avoid the wave deflection problem on the boundary surfaces.

Numerical Modeling

The simulations are conducted using the general purpose finite element code ABAQUS/Explicit (2007). The analysis is performed by employing a 3D material model to determine the behavior of concrete. The nonlinear analysis are performed by the allowance of local failure (i.e., cracking) being reached. Both the concrete specimen and SHPB are modeled using Lagrangian brick element for accurate, stable and quick solution. Reduced integration uses a lower-order integration to form element stiffness. To control hourglassing problem with first-order, reduced integration element C3D8R (8-node linear brick, reduced integration, hourglass control) is used in stress/displacement analysis ABAQUS/Explicit (2007). In addition, this type of element is suitable for reasonably fine meshes model and provides accurate results. Therefore, the selected meshes for both the concrete specimen and SHPB are structural hex shape, geometrically linear with element type C3D8R. Usually, dense FE meshes are preferred in order to model concrete with several investigations (Grote *et al*., 2001; Li and Meng, 2003) adopting FE analysis as small as 2-3 mm. Hence, finer meshes are adopted in the present study and shown in Table 2.

Table 2: Element type, global size of SHPB and concrete specimen

Components of SHPB	Type of elements	Global size	Node
Striker bar	C3D8R	0.0085	8
Input bar	C3D8R	0.0085	8
Output bar	C3D8R	0.0085	8
Specimen of concrete	C3D8R	0.0051	8
Fixed end of output bar	C3D8R	0.0100	8

RESULTS AND DISCUSSION

The results and discussion are organized and presented on focusing firstly, the peak stress intensity and finally, the stress-strain behavior of concrete.

The Peak Stress Intensity

The results of three different strain rates are presented in the deformable shape of contour plot sequentially. Figure 2a and b show that the comparatively low stress intensity in the center of specimen appearing the pink color while the applied strain rate 300 sec^{-1}. The concrete specimen appears red and pink colors (medium intensity of stress) at the center of the specimen and bright green color in a small part of outer surface of those specimens during the impact loading under strain rates 350 and 500 sec^{-1} as shown in Fig. 3a and b. In addition, the failure of concrete occurs showing blue color (low stress intensity of stress) at the center of the specimen and bright green color (maximum intensity of stress) almost the whole outer surface of concrete specimens as shown in Fig. 4a and b. Hence, the numerical prediction reveals that with the increase of loading rate the failure of concrete accelerate rapidly of the outer surface.

The occurrence of peak stress depends on the stress wave propagation through concrete specimen. Therefore, the internal stress field within the concrete specimen is frequently changed within very short period of time. Figure 5a-d show stress intensities that developed in the concrete specimen with respect to the time after the impact. The result reveals that the failures of the concrete materials occur at 0.0013 sec against the strain rate 350 sec^{-1}.

Stress-Strain Behavior

The result shows that the maximum stress are 28.6, 39.9, 76.3 MPa, at the ultimate strains 0.0055, 0.0077 and 0.011 corresponding to the strain rate 350, 500 and 700 sec^{-1}, respectively in Fig. 6. This result indicates that both the stress and strain increase with the increase in strain rate. Figure 6 clearly shows that the concrete attributes elastic behavior before reaching the yield stress and it shows plastic behavior after immediately reaching the maximum stress.

The numerical results compared with the experimental work which was conducted in the laboratory in order to verify the accuracy. The predicted numerical investigation agreed with the experimental results attributing some degree of deviation. The variations are 50.26, 46.8 and 26.6% corresponding to the strain rate of 350, 500 and 700 sec^{-1}, respectively in Table 3. In general, the concrete failure model would be analyzed in the plastic range for an accurate numerical result under high strain rate. In this study, the model was developed considering the elastic properties of concrete which was the main cause of deviation between the numerical and experimental results. Furthermore, the deviation may occur due to the concrete specimen lost the load bearing capacity within the short period of time as indicated in Fig. 5 and immediately changed behavior from elastic state to plastic state showed in

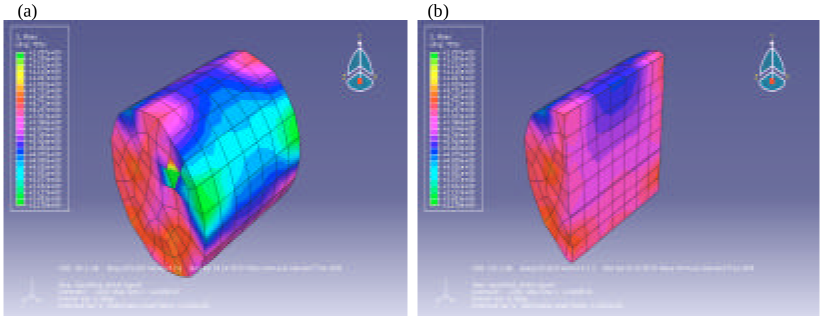

Fig. 2: (a) Stress intensities of concrete cylinder under the strain rate 350 $\sec^{-1}$ and (b) impact velocity of striker bar 12.6 m $\sec^{-1}$

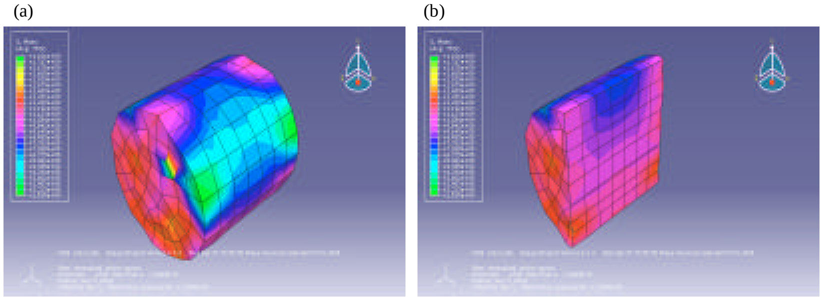

Fig. 3: (a) Stress intensities of concrete cylinder under the strain rate 500 $\sec^{-1}$ and (b) impact velocity of striker bar 18 m $\sec^{-1}$

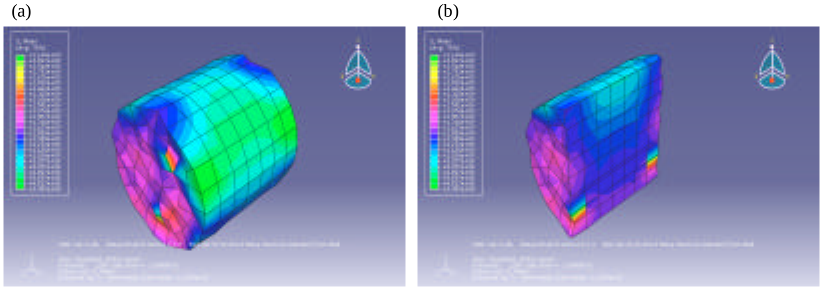

Fig. 4: (a) Stress intensities of concrete cylinder under the strain rate 700 $\sec^{-1}$ and (b) impact velocity of striker bar 25.2 m $\sec^{-1}$

Fig. 6. The analysis are carried out assuming the elastic properties of concrete that affect the present numerical results. Therefore, plastic properties of concrete can be used to investigate the dynamic behavior in order to predict the accurate results.

Hentz *et al.* (2004) had conducted experiment and performed simulation with three loading rate at 350, 500 and 700 $\sec^{-1}$ and used the discrete element method. Their experimental result particularly the curves were well fitted in the pre-peak region and the deviation is observed in the lower part of the graph. The discrete element method had succeeded to investigate the transient phenomena. On the other hand, the present

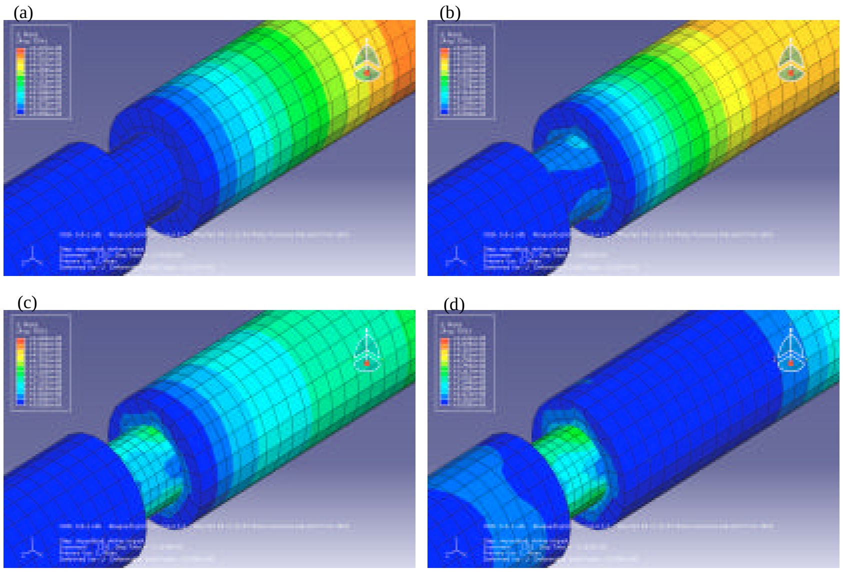

Fig. 5: Evaluation stress intensity of concrete during the impact. (a) t = 0.0009 sec, (b) t = 0.0010 sec, (c) t = 0.0011 sec and (d) t = 0.0013 sec against the strain rate 350 sec^{-1}

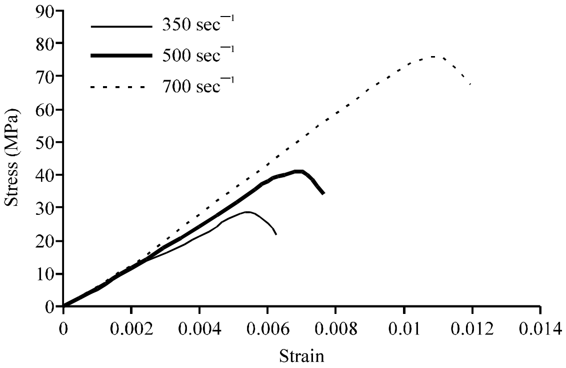

Fig. 6: Stress-strain behavior of concrete with different strain rate

Table 3: Comparison between the simulated and experimental results of concrete

	The peak stress (MPa)		
Strain rate (sec^{-1})	Experimental	Simulation	Percent deviation
350	57.5	28.6	50.3
500	75.0	39.9	46.8
700	104.0	76.3	26.6

model with elastic properties of concrete is unable to completely satisfy the experimental results due to the analysis were not performed considering the plastic behavior of concrete.

The numerical results reported by Georgin and Reynouard (2003) with a viscoplastic hydrostatic pressure-dependent model showed differences between the numerical simulation and the experiment due the inertia, rate effect, frictional and confinements effect. The aim of that study was to understand and to evaluate the rate effect other than to predict the material response. Finally, the study had concluded that the numerical simulations of the SHPB test give the idea about the dynamic behavior of concrete only. Similarly, the present simulation with elastic properties of concrete has provided the idea about the deviation between the numerical and experimental results. It also provided the direction to select the right model in order to obtain accurate result for further study in the future.

CONCLUSIONS

This study is carried out with three dimensional elastic model of NSC based on the finite element method. Although, the results show some degree of deviation, the present simulation process is capable to predict the dynamic behavior of NSC. From this study, the following conclusion can be drawn:

- The peak stresses of cylindrical NSC specimens are 28.6, 39.9 and 76.3 MPa while the maximum strains are 0.0055, 0.0077 and 0.011, respectively. The peak stress increased 41 and 91% from the value of 28.6 MPa peak stress at 350 sec^{-1} by the application of strain rate at 500 and 700 sec^{-1}
- The comparative study shows +50.26, +46.8 and +26.6% deviation from the numerical results regarding to the strain rate of 350, 500 and 700 sec^{-1}, respectively. The dynamic properties of NSC are affected by strain rate, elasticity and rapidly changed from elastic to plastic state at time of failure. Therefore, the analysis can be performed in the range of plastic state in order to predict the dynamic behavior of concrete

ACKNOWLEDGMENTS

The authors would like to thank to the Ministry of Higher Learning Malaysia for the financial support under grant UKM-KK-02-FRGS0014-2006. Also, the authors would like to thank the staff of Concrete and Computer Laboratory, Universiti Kebangsaan Malaysia for their support and providing access to the required materials for the completion of this study.

REFERENCES

ABAQUS/Explicit, 2007. User Manual, V. I, II, III and IV. Version 6.7, Hibbitt, Karlsson and Srensen Inc., USA.

Donze, S., A. Magnier, L. Daudeville, C. Mariotti and L. Davenne, 1999. Numerical study of compressive behavior of concrete at high strain rates. J. Eng. Mech., 125: 1154-1163.

Georgin, J.F. and J.M. Reynouard, 2003. Modeling of structures subjected to impact: Concrete behavior under high strain rate. Cement Concrete Composites, 25: 131-143.

Grote, D.L., S.W. Park and M. Zhou, 2001. Dynamic behavior of concrete at high strain rates and pressures: I. Experimental characterization. Int. J. Impact Eng., 25: 869-886.

Hentz, S., F.V. Donzé and L. Daudeville, 2004. Discrete element modelling of concrete submitted to dynamic loading at high strain rates. Comput. Struct., 8: 29-30.

Krauthammer, T., M.M. Elfahal, J. Lim, T. Ohno, M. Beppu and G. Markeset, 2003. Size effect for high-strength concrete cylinders subjected to axial impact. Int. J. Impact Eng., 28: 1001-1016.

Li, Q.M. and H. Meng, 2003. About the dynamic strength enhancement of concrete-like materials in a split hopkinson pressure bar test. Int. J. Solids Struct., 40: 343-360.

Riisgaard, B., T. Ngo, P. Mendis, C.T. Georgakis and H. Stang, 2007. Dynamic increase factors for high performance concrete in compression using split hopkinson pressure bar. Proceedings of the International Conference of Fracture Mechanics of Concrete and Concrete Structures, (ICRMCCS'07), Italy, pp: 1-4.

Rossi, P., J.G.M. van Mier, C. Boulay and L.F. Maou, 1992. The dynamic behaviour of concrete: Influence of free water. Mater. Struct., 25: 509-514.

Schuler, H. and H. Hakan, 2006. Fracture behavior of High Performance Concrete (HPC) investigated with a hopkinson-bar. J. Phys., 134: 1145-1151.