Journal of Applied Mechanics Vol.7,pp.635-642 (August 2004) JSCE

Numerical Simulation of a Concrete Plate subjected to Impact Load

Stefan Szyniszewski*, Tomoya Akada**, Hiroshi Masuya***, Yasua Kajikawa***

* Mr. of Eng., Graduate School of Natural Science & Technology, Kanazawa University, 2-40-20, Kodatsuno, Kanazawa 920-8667
** M. of Eng., Dept. of Construction, Fukui City, 3-10-1, Ohte, Fukui 910-8511
*** Professor, Graduate School of Natural Science & Technology, Kanazawa University, 2-40-20, Kodatsuno, Kanazawa 920-8667

The behavior of a concrete plate under impact load with its numerical simulation is herein presented in this paper. In order to obtain experimental data an impact experiment was conducted. The experimental behavior of the investigated plate and its failure modes are observed and described. Furthermore, a numerical simulation of the impact phenomenon using F.E.M software, ADINA (Automatic Dynamic Incremental Nonlinear Analysis), is performed. An analysis of influence of input parameters on the analysis results is presented. Moreover, after consideration, which material parameters have significant influence on the analytical results and some conclusions regarding concrete plate's behavior are made.

Key Words: impact, concrete plate, experiment, finite element method, ADINA

1. Introduction

One of the most important dynamic problems in civil engineering is the behavior of the building materials (such as concrete) and structural elements under the impact load. Civil Engineers encounter impact problems on a great variety of occasions, such as e.g.:

- Vehicle impact against a bridge pier, a column or a barrier,
- Rock shelter structures (rock shed) over roads in mountain areas,
- Aircraft crashes on a nuclear power plant,
- Miscellaneous.

Generally the dynamic behavior of a structure and structural members under impact differs from that of static. Moreover, there have been many diverse problems, since this behavior is complex. The reproducibility of experimental results under impact is important. However it has become apparent that the results, even retrieved under the same conditions, are not in a sufficient agreement. A recent development of measurement apparatus is remarkable. The explication of an impact phenomenon is becoming reliable. The Research Subcommittee of Japan Society of Civil Engineers for Standardization of Method of Shock Experimenting and Analyzing has performed an examination of impact experimental techniques as one of the most important subjects[1]. We also have achieved many impact experiments[2]. From the investigation of those results, we have already clarified the fundamental knowledge about the experimental techniques and the measuring methods.

On the other hand, a reliable numerical analytical method is required only to complement the rack of experimental results. This method is also used to establish a design method for a structure under shock. One of the authors checked the validity and the reproducibility of a numerical analysis technique using the distinct element method[3]. The validity and the reproducibility were verified by the consistency with the experimental results. In this study, we have achieved a series of fundamental simulations for a concrete plate using the program of the finite element method program ADINA (Automatic Dynamic Incremental Nonlinear Analysis). The analysis aims at the explication of concrete's plate impact behavior, because a concrete plate is one of the most fundamental structural members. Investigated results, and numerical characteristics with relation to experimental results are herein presented in this paper. In addition, the validity of this simulation method is checked. Moreover the discussion for further investigation of the general impact behavior of a plate, aiming at the establishment of a design method of a plate structure under impact are shown.

2. Experiment

In order to investigate concrete's behavior under impact load with stress distribution corresponding to the real structural members, the plate specimens are tested (see Fig.1). During the experiment, investigated plates were loaded by the free-fall mass, which was dropped from the specific height, than guided by the steel pipe and finally impacted the plate in its center with the velocity of 6.71 [m/s]. A description of the experimental device is shown in Fig.2. The plate was constrained by a steel frame with the aim of obtaining free support conditions. The impact load is transmitted from the falling missile, through the load cell, to the steel missile acting on the plate. Due to the existence of the load cell, a load-time history of impact load is recorded. To clear the recorded data from noises and inaccuracies, a 6-point average method with smoothing techniques were used (Fig.3).

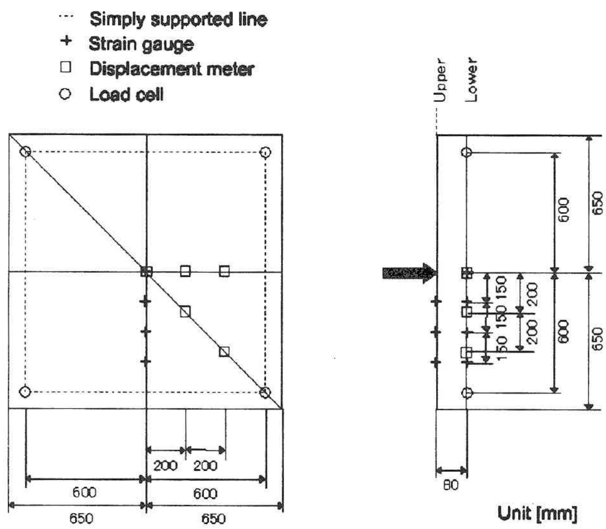


Fig.1 Investigated plate

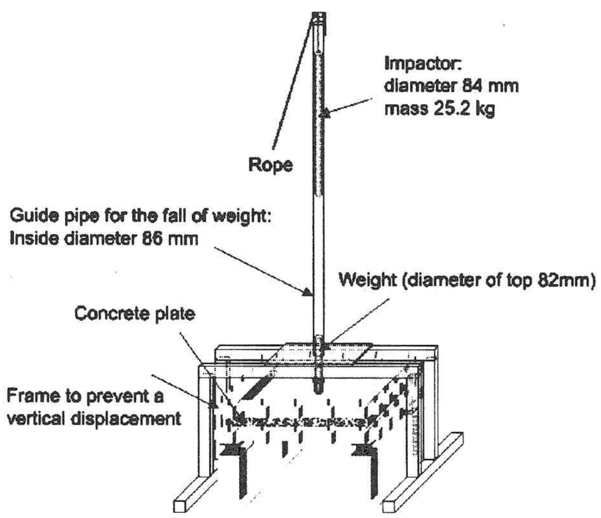


Fig.2 Experimental device

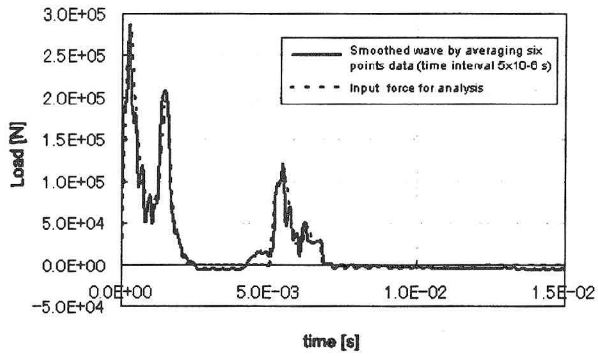
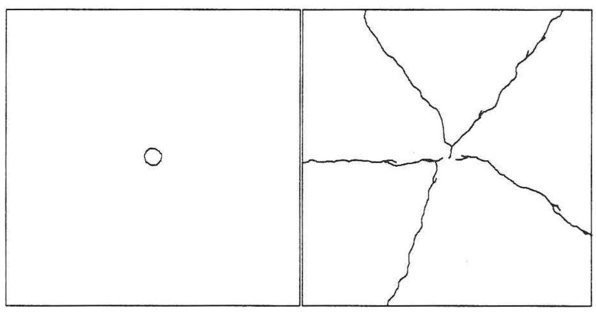


Fig.3 Load-time history recorded during the experiment

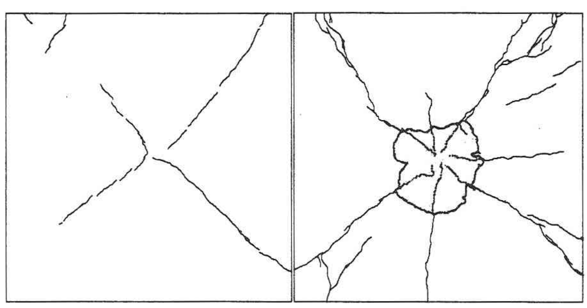
3. Experimental results

A concrete plate was subjected to static and impact tests. After static loading, crack patterns and failure mode are obtained as in Fig.4. An impact load causes scabbing of the concrete plate from the bottom face, exactly below the impact point. Crack distribution and failure mode is presented in Fig. 5. It is observed that failure mode is dangerous, because impact produces a peeling off from the back face of the plate opposite to the impact face, which in the real structure can cause loss of lives and property.



Top face Bottom face

Fig.4 Failure mode of the plain concrete plate, static test



Top face Bottom face

Fig.5 Failure mode of the plain concrete plate, impact test

4. Numerical model of concrete plate under impact

In order to optimally use the computer resources, concrete plate's symmetry is taken into account and therefore only a quarter of the investigated plate is simulated, as shown below in Fig.6.

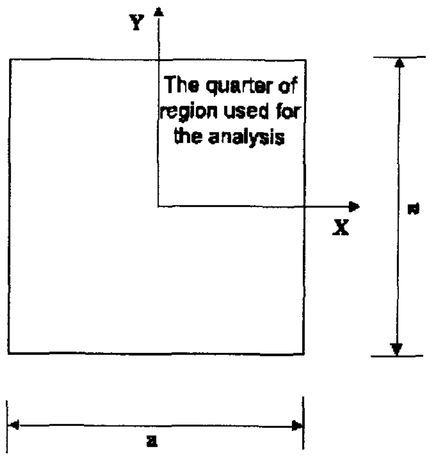


Fig.6 Plate's quarter considered in the simulation

Numerical model is created in ADINA. Sometimes a division manner is recommended in order to avoid excessive stress concentration in the loading point and related numerical difficulties, therefore a rather coarse mesh is proposed. In this study, we adapted the model throughout some trials and errors so that the concrete plate is divided into 26x26x4=2704, 3-D solid, elements with eight nodes, as shown in Fig.7 below:

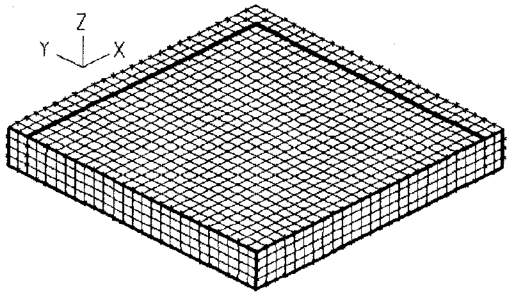


Fig.7 F.E.M. model of quarter of the investigated plate

Impact influence on the plate is modeled as a time dependent, uniformly distributed load, which is subjected to the plate's center. In the simulation, the load is subjected to the element, which lies in the corner of the plate's quarter, corresponding to the plate's center. The dimension of the element is 25x25x20 [mm]. Therefore, for a whole model, the impact load is distributed on an area of 50x50=2500 [mm^2], which is situated in the plate's center.

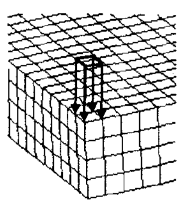


Fig.8 Load pattern applied in the analysis

5. Material model and parameters

For the analysis only material parameters, obtained form static tests, were available. In the experiment a high strength concrete material was used. Its characteristics are shown in Table 1. Therefore, a concrete material model, supplied by ADINA, is used in the simulation. ADINA's concrete model proposes the following stress-strain relation:

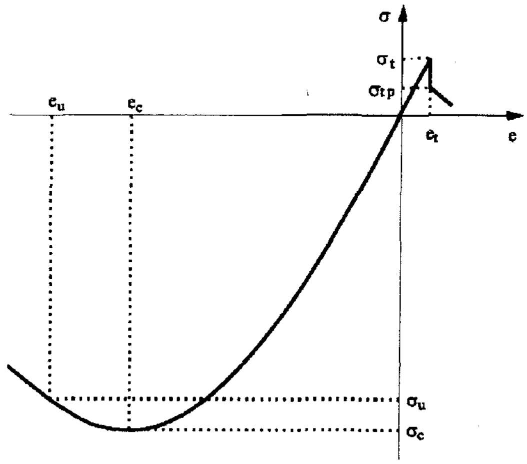


Fig.9 Stress-strain relation for the concrete material

An initial tangent Young's modulus is $E=3.35x10^{10}$ [N/m^2] and a Poisson ratio is ν =0.21.

Table 1 Material parameters of concrete

E [N/m^2]	3.35E+10
ν	0.21
σ_t [N/m^2]	6.74E+06
σ_{tp} [N/m^2]	3.37E+06
σ_c [N/m^2]	-6.95E+07
e_c	-0.0028
σ_u [N/m^2]	-5.00E+07
e_u	-0.005

The concrete's strain rate effect is not included in the analysis. The authors did not have any material data from dynamic material tests therefore manipulation with the static material parameters could have only a numerical sense and could have been only a parametric analysis. The tensile material parameters, which are the most significant for the analysis, as it shown further, were obtained in the split test. The test is static and tensile material data are obtained from the compressive test of a cylindrical specimen of height 200 [mm] and a diameter of 100 [mm]. The test was made according to specification JIS A 1132.

The stress-strain relation assumes monotonic loading conditions. For unloading conditions and loading back to the stress state from which unloading occurred, the initial Young's modulus E_0 is used. For strain states beyond e_u in compression, is assumed that stresses are linearly released to zero, using the following modulus:

$$E_u = \frac{\sigma_u - \sigma_c}{e_u - e_c} \quad (1)$$

Numerical value C_{TSD} (constant for tensile strain definition) is a user input variable that defines the amount of tension stiffening. It is defined in Fig. 10:

$$C_{TSD} = \frac{e_m}{e_t} \quad (2)$$

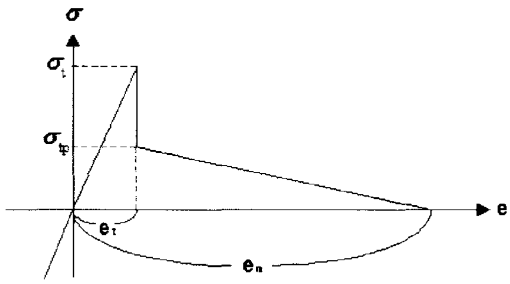


Fig.10 Constant for tensile strain definition

It is important to mention that ADINA's concrete model includes post tensile and post compression cracking behavior. Once a tensile plane of failure has formed, it is checked in each subsequent solution step to see whether the failure is still active. The failure is considered to be inactive provided the normal strain across the plane becomes negative and less than the strain at which the "last" failure occurred. It is otherwise active. Therefore, a tensile failure plane can repeatedly be active and inactive. Analogously, if the material has crushed in compression, it is assumed that the material strain-softens in all directions. At any time during post-crushing calculations, if any one of the principal stresses checked individually reaches a positive value, this stress is set to zero.

Under multiaxial stress conditions the compression and tensile cracking behavior is identified using the multiaxial failure envelope, and once the material has crushed, isotropic conditions are assumed.

A description of the post compression or tensile cracking behavior requires additional input parameters, which are not available after static, standardized material test, namely: η_n stiffness and η_s shear reduction factors, respectively. Typically, η_n=0.0001 and η_s=0.5. The factor η_n is not exactly equal to zero in order to avoid the possibility of a singular stiffness matrix. The factor η_s depends on a number of physical factors and therefore its value can be chose according the researcher's judgment.

Damping effects are not taken into consideration by the parameters of this experiment.

6. Numerical analysis of concrete plate under impact

After the above described steps, the numerical analysis in terms of ADINA is run. In order to evaluate the numerical results, the deflection of the central point on the bottom face of concrete plate as a function of time, is compared to the recorded, experimental displacement-time history. This comparison is assumed as the evaluation criterion for the numerical analysis run in ADINA.

The values of the stiffness and shear reduction factors are input, as they are proposed by ADINA's authors, namely η_n=0.0001 and η_s=0.5.

In the first stage the time step interval is investigated. In order to check its influence the following 3 different time intervals are examined (see Table 2):

Table 2 Time step interval table

CASE	A	B	C
σ_t [N/m^2]	6.74E+06	6.74E+06	6.74E+06
σ_{tp} [N/m^2]	3.37E+06	3.37E+06	3.37E+06
σ_c [N/m^2]	-6.95E+07	-6.95E+07	-6.95E+07
e_c	-0.0028	-0.0028	-0.0028
σ_u [N/m^2]	-5.00E+07	-5.00E+07	-5.00E+07
e_u	-0.005	-0.005	-0.005
Time step	0.125 ms	**0.10 ms**	**0.05 ms**

The following displacement-time history, as shown in Fig. 11, is obtained:

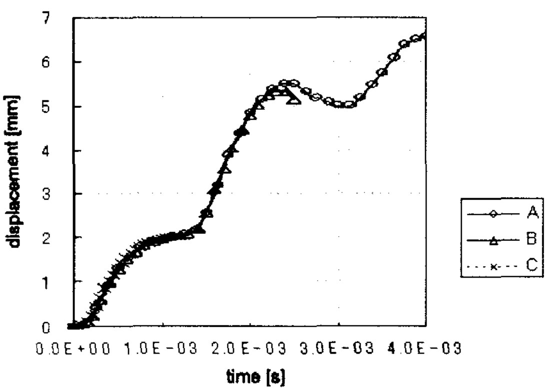


Fig.11 The influence of time step interval

When the time step interval is too small the analysis crashes after 1.5e-3 [s] for the curve C and after 2.5e-3 [s] for the curve B. In spite of the numerical problems, the influence of time step interval on the shape of deflection-time curve is not remarkable, therefore for the analysis Δt=0.125 [ms] is set.

In the second stage, an influence of the constant for tensile strain definition is investigated. The values of the C_{TSD} are inputted as shown in Table 3:

Table 3 Input values of the C_{TSD}

CASE	A	B	C
σ_t [N/m^2]	6.74E+06	6.74E+06	6.74E+06
σ_{tp} [N/m^2]	3.37E+06	3.37E+06	3.37E+06
σ_c [N/m^2]	-6.95E+07	-6.95E+07	-6.95E+07
e_c	-0.0028	-0.0028	-0.0028
σ_u [N/m^2]	-5.00E+07	-5.00E+07	-5.00E+07
e_u	-0.005	-0.005	-0.005
C_{TSD}	100	**1000**	**10**

Input values of the C_{TSD} affect the displacement-time history as shown in figure 12:

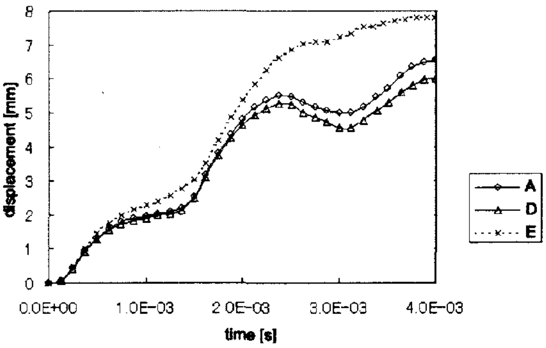


Fig.12 Influence of the C_{TSD}

As it is shown in Fig.12, increase of the C_{TSD} strengthens the concrete and decreases deflection of the central point.

The best agreement with the experimental data is obtained for the C_{TSD}=100.

In the next stage, an influence of strength parameters is investigated. Firstly, compressive parameters, like σ_c, σ_u and e_u are manipulated, as it is presented in the Table 4:

Table 4 Investigated compressive material parameters

CASE	A	F	G	H
σ_t [N/m^2]	6.74E+06	6.74E+06	6.74E+06	6.74E+06
σ_{tp} [N/m^2]	3.37E+06	3.37E+06	3.37E+06	3.37E+06
σ_c [N/m^2]	-6.95E+07	-6.95E+07	-6.95E+07	**-8.00E+07**
e_c	-0.0028	-0.0028	-0.0028	-0.0028
σ_u [N/m^2]	-5.00E+07	-5.00E+07	**-3.00E+07**	-5.00E+07
e_u	-0.005	**-0.008**	**-0.015**	-0.005

For the investigated compressive material parameters, deflection-time history is shown in Fig.13:

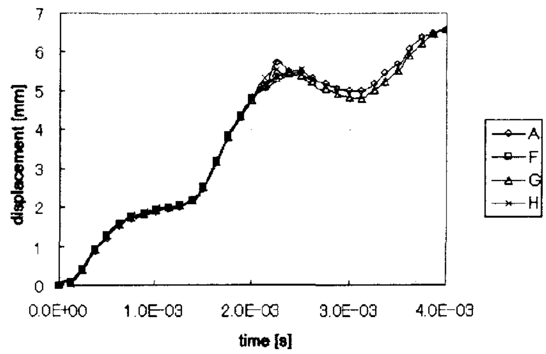


Fig.13 Influence of the compressive material parameters

The influence of the compressive material parameters is not significant for the deflection-time history. All the curves in Fig.13 are very similar in spite of variation of one or two compressive parameters in Table 4.

A role of the post-cracking tensile material parameters is investigated. The following parameters are varied (see Table 5):

Table 5 Investigated post-cracking tensile material parameters

CASE	A	I	J
σ_t [N/m^2]	6.74E+06	6.74E+06	6.74E+06
σ_{tp} [N/m^2]	3.37E+06	**6.67E+06**	**5.00E+06**
σ_c [N/m^2]	-6.95E+07	-6.95E+07	-6.95E+07
e_c	-0.0028	-0.0028	-0.0028
σ_u [N/m^2]	-5.00E+07	-5.00E+07	-5.00E+07
e_u	-0.005	-0.005	-0.005

For the investigated post-cracking tensile parameters, deflection-time history is shown in Fig.14:

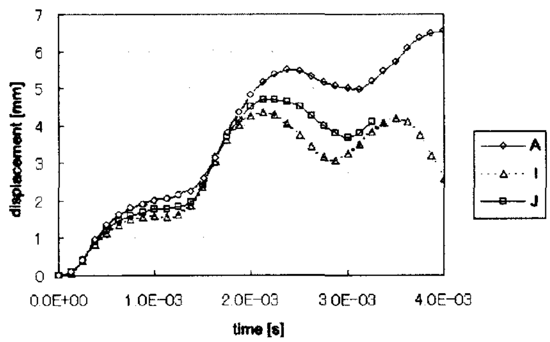


Fig.14 Influence of the post-cracking tensile parameters

Moreover, the following general tensile parameters, presented in Table 6, are investigated:

Table 6 Investigated tensile material parameters

CASE	A	K	L
σ_t [N/m^2]	6.74E+06	**1.35+07**	**2.02E+07**
σ_{tp} [N/m^2]	3.37E+06	**6.74E+06**	**1.01E+06**
σ_c [N/m^2]	-6.95E+07	-6.95E+07	-6.95E+07
e_c	-0.0028	-0.0028	-0.0028
σ_u [N/m^2]	-5.00E+07	-5.00E+07	-5.00E+07
e_u	-0.005	-0.005	-0.005

For the investigated tensile material parameters, deflection-time history is shown in Fig.15:

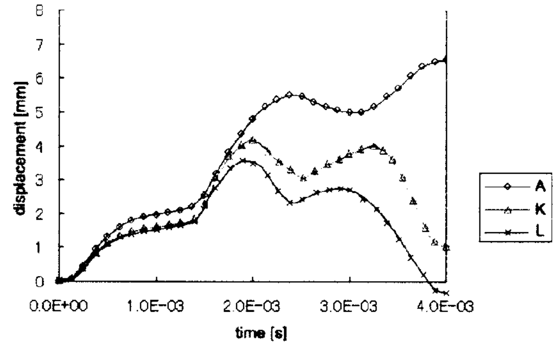


Fig.15 Influence of the tensile material parameters

The influence of the tensile material parameters is significant for the deflection-time history. It is observed that tensile material parameters of concrete play an important role in its behavior under impact in contrast to compressive material properties. Therefore, failure mode and concrete's behavior is strongly dependent on the tensile properties of concrete.

Finally, after analysis of the finite element method input parameters, the behavior of concrete plate under impact is simulated. A satisfactory agreement between numerical and experimental results is observed in the first 4 [ms] as it is shown in Fig.16:

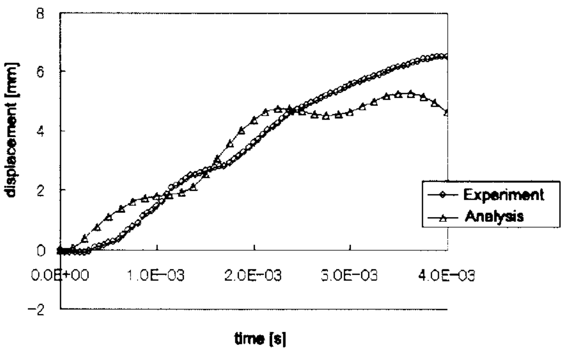


Fig.16 Comparison of experimental and simulated deflection-time history of the central point of bottom plate's face for CASE A

Unfortunately, the full deflection-time history doesn't exhibit a satisfactory agreement with the experimentally recorded deflection-time history.

7. Crack distribution

The ADINA enables to plot crack propagation in consecutive steps of analysis. Crack propagation, both under static and impact load, exhibits satisfactory agreement with crack patterns, observed during experiments. Crack patterns obtained in the static finite element simulation are presented in Fig.17-20:

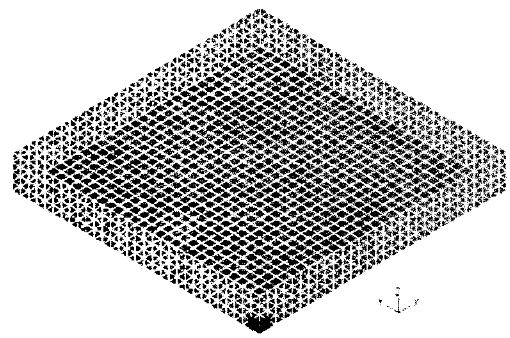


Fig.17 Open cracks under static load P=1.20x10^4[N] after 0.30[s] from the start of the load

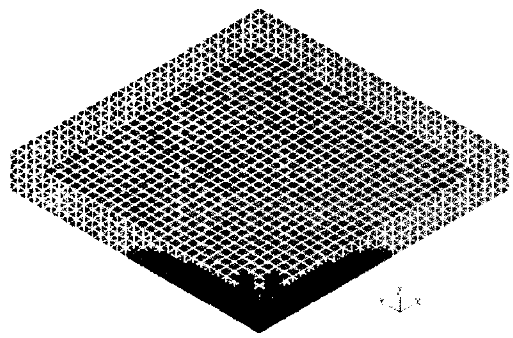


Fig.18 Open cracks under static load P=1.2x10^4[N] after 0.45[s] from the start of the load

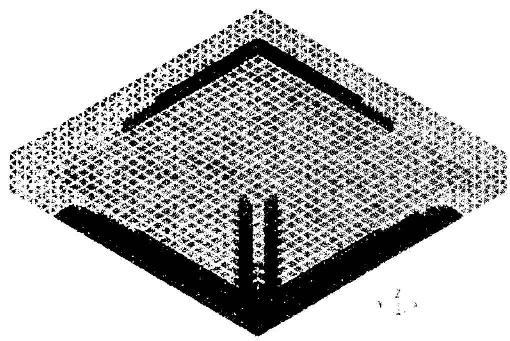


Fig.19 Open cracks under static load P=2.40x10^4[N] after 0.60[s] from the start of the load

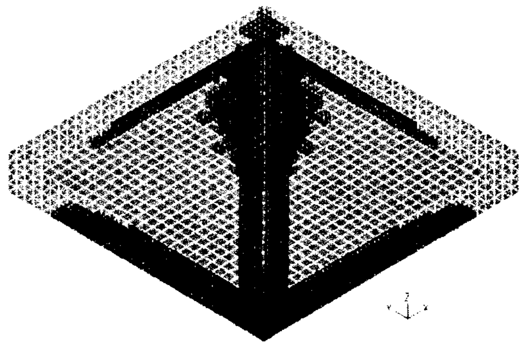


Fig.20 Open cracks under static load P=2.56x10^4[N] after 0.64[s] from the start of the load

The simulated crack distribution under static load corresponds to crack pattern, which is recorded during the static test.

Crack patterns obtained in the dynamic finite element simulation of a concrete plate under impact load are shown in Fig.21-22:

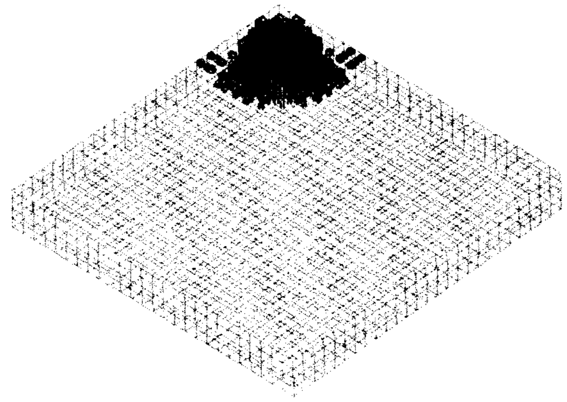


Fig.21 Open cracks under impact load after 0.2 [ms] from the start of the load

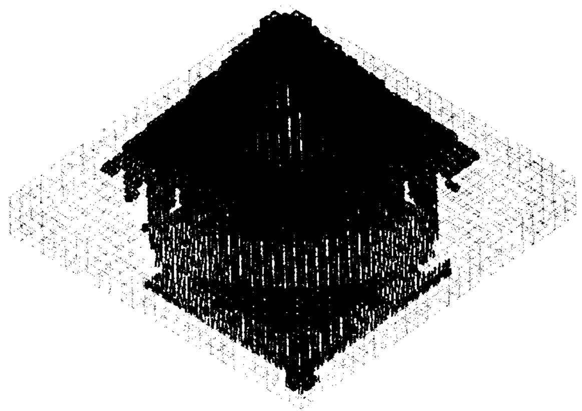


Fig.22 Open cracks under impact load after 1.125 [ms] from the start of the load

As it is shown in Fig.21-22, simulated crack patterns in the consecutive time steps exhibit tendency to form 3 main cracks, which start from the loading region and widespread along two boundary surfaces and along hypotenuse of a concrete plate. The crack's concentration is the most intense in the surroundings of impact region. This tendency is in fully agreement with the experimental observations, which are shown in Fig.5.

8. Concluding remarks

In this study we have achieved a series of fundamental simulations for a plain concrete plate by the code of the finite element method ADINA, aiming at the explication of the impact behavior. Investigated results concerning numerical characteristics with experimental results are herein presented in this paper. The results obtained by this study are concluded as follows:

1) The post-cracking behavior seems to be mesh-dependent, therefore in order to avoid numerical difficulties, like abnormal mesh distortion in regions of irregular meshing, a very regular and uniformly distributed mesh pattern is recommended.
2) In the conducted experiment, the free fall mass has a rather sharp contact shape and initial contact region is very small in comparison to the plate's dimensions. Therefore, contact models, which seem to be very realistic, can cause abnormal deformations of loaded elements in the impact region and therefore cause a crash of analysis
3) A post-cracking behavior require additional input parameters, namely η_n, η_s (post-cracking stiffness and shear reduction factors) and C_{TSD} (constant for tensile strain definition), which are not available as experimental data. To eliminate values, which are not measured experimentally and have only numerical meaning, some improvement could be achieved if fracture energy is used as an alternative input for post-cracking behavior.
4) It is observed that tensile material parameters, both tensile strength and post cracking material parameters have significant influence on the analysis' results and are responsible for the failure mode of the investigated concrete plate.

In order to improve the impact analysis in the future research and obtain a better agreement with the experimental data within time longer than 4[ms], it seems necessary to consider the following points:

- The influence of strain-stress rate and eligibility of strength material parameters from static tests
- The post-cracking behavior and its relation with a quality of mesh and mesh distribution

- A definition of fracture energy in an impact analysis should be formulated.

Acknowledgment

We would like to express sincere thanks to Mr. A. Kubota for the assist of pursuit of this study and to Nihon Samicon ltd. for the offer of specimens.

References

1) The Research Subcommittee of Japan Society of Civil Engineers for Standardization of Method of Shock Experimenting and Analyzing, *Progress report of research, Proceedings of 5th symposium concerning impact problems,* Division II, Japan Society of Civil Engineers, 2000

2) Masuya H., Nakata Y., Kajikawa Y., *The application of the distinct element method to impact problems,* Journal of Japan Society of Civil Engineers, Vol.38A, pp.1477-1487, 1992

3) Masuya H., Nakata Y., Kajikawa Y., Morishima Y., *On application of the distinct element method to the analysis of behavior of reinforced concrete beam under impact,* Proceedings of 2nd Asia-Pacific conference on shock & impact loads on structures, Melbourne, Australia, pp.341-348, 1997.

(Received: April 16, 2004)