コンクリート工学年次論文報告集 11-2 1989

論 文

[2108] Non-Linear Dynamic Analysis and Evaluation of Impact Resistance of Reinforced Concrete Slabs under Impulsive Load

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1. INTRODUCTION

A large number of structures such as nuclear power reactors, offshore structures and barges can be constructed using concrete. The occurrence of an accidental impact to such structures of significant importance is very rare but nevertheless, precautions are necessary. The ultimate behaviour of structures is of much importance when studying these cases. In this study, slabs consisting of two materials were subjected to impulsive loads to verify the applicability of the layered finite element method. Also, an evaluation method on impact resistance for different materials was considered with the possibility of application to design in future.

2. ANALYTICAL METHOD

A non-linear dynamic finite element method was used to study the ultimate behaviour of reinforced concrete slabs subjected to impulsive loads. In order to evaluate the impact resistance of a structure, it is necessary to be able to predict the ultimate behaviours.

2.1 FINITE ELEMENT MODEL FOR RC SLABS

Reinforced concrete slabs with doubly reinforced section were modelled using the layered finite element procedure [1,2] as shown in FIG.1 (1/4 size). The 4 node rectangular plate bending element was applied to the dynamic non-linear analysis [3,4]. The element nodal-point degree of freedom are the transverse displacement ω and sectional rotations θ_x and θ_y . The slabs consisted of 8 layers, 6 of concrete and 2 of reinforcement. This method has the advantage of assuming different material properties for each layer. The following mechanical properties were assumed for this analysis :

(1) Strain in the reinforcement and concrete layers is assumed to be proportional to the distance from the neutral axis.

(2) The slab is made up of hypothetical concrete layers and reinforcement layers which resist axial and shear forces in the in-plane direction.

(3) Concrete layers are in the state of plane stress and there is no slip between layers.

(4) Bending moment acts through the centre of the elastic regions and the

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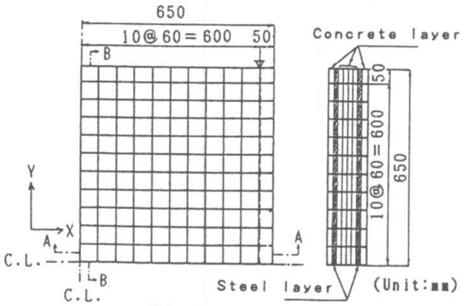
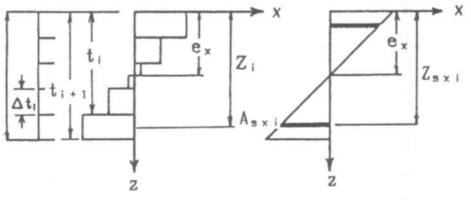


(Plan) (Section B-B)

FIG.1 Layered finite element meshes for RC slab (1/4 sect.)



(a) Concrete layer (b) Reinforcement layer

FIG.2 Strain in concrete and reinforcement layers

effects of in-plane forces are not considered here.

(5) Concrete is considered to be an isotropic material after cracking.

(6) Material properties obtained from static uniaxial test are used as input data.

Impulsive load-time functions derived from experiments were used as the input data for load. Strain distribution through the section was assumed to be as shown in FIG.2. The neutral axis can be given by the following equations:

$$e_x = \frac{1/2 E_c \cdot t^2 + E_s \cdot \Sigma A_{sxi} \cdot Z_{sxi}}{E_c \cdot t + E_s \cdot \Sigma A_{sxi}}, \quad e_y = \frac{1/2 E_c \cdot t^2 + E_s \cdot \Sigma A_{syi} \cdot Z_{syi}}{E_c \cdot t + E_s \cdot \Sigma A_{syi}} \qquad (1)$$

where,

e_x, e_y : the neutral axes in the x and y directions, respectively.
E_c, E_s : concrete and reinforcement moduli of elasticity, respectively.
A_{sxi}, A_{syi} : average cross-section per unit length in the x, y directions for the i th layer of reinforcement, respectively.
Z_{sxi}, Z_{syi} : distance from the middle of i th layer to the top surface of slab in the x, y directions, respectively.
t : slab thickness

The consistency mass matrix was applied together with the nonconforming plate bending element. Different time increments (Δt) were used in the integration process and the ones which were found to provide stable values were selected.(Δt =50 μsec for failure and Δt =200 μsec for elastic analysis).

2.2 VERIFICATION TESTS

In order to verify the accuracy of the analysis, comparisons with test results were carried out. Slabs with a dimension of 130 x 130 x 13cm were subjected to elastic tests and also failure tests. The slabs had two different layers with the top layer (front face; layers 1,3,4 and 5 in FIG.1) being normal strength concrete and the bottom layer (rear face, layers 6 and 8 in FIG.1) being steel fibre reinforced concrete. The purpose of using such a slab was not only to verify whether the analytical procedure is suitable for slabs with different materials but also because steel fibre is capable of reducing the amount of scabbing and control cracking.

The apparatus used for the impulsive test was a pendulum type impact testing machine which was specially designed to derive only one wave impact (see FIG.3). The falling weight had a mass of 500kgf. In order to derive soft impacts, a rubber pad was placed on a square steel plate (15 x 15 x

1cm) at the impact face. It is known that the loading rate varies with the thickness of the rubber pad. Two tests were carried out with the rubber pad being 1cm (D-1 slab) and 2cm (D-2 slab). The impulsive load-time relation was measured by acceleration sensors attached to the falling mass. Measurements for deflection, acceleration response and cracks were carried out. The measuring system consisted of non-contact displacement transducers, acceleration sensors, crack gauges and an analog data recorder.

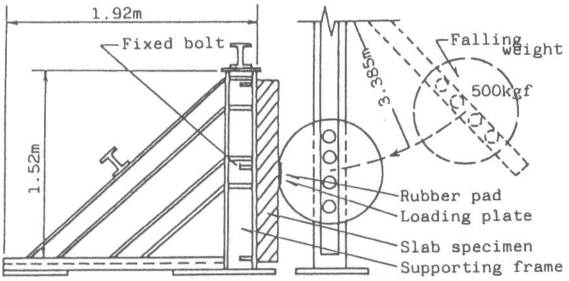


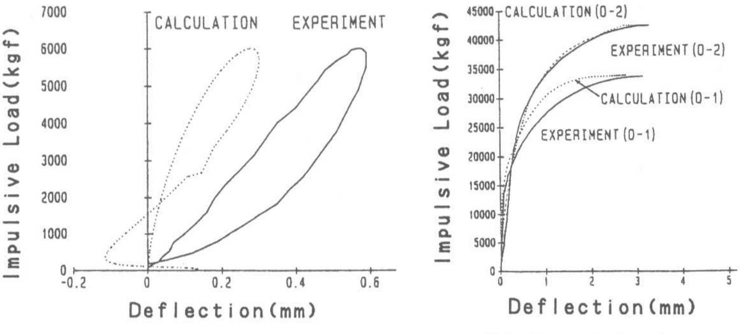
FIG.3 Testing apparatus for impulsive load

For tests within the elastic region, the height of fall was set at 3cm. The height of fall for the failure tests under one single impulsive blow was first estimated by means of the above method of analysis. The material properties and impulsive force-time relation were assumed based on results of previous experiments [5]. Based on the assumption that the failure energy is totally transferred to the slab during impact, the height of fall was estimated (100cm for D-1 and 170cm for D-2). Furthermore, static tests were carried out on other slabs in order to be able to distinguish the difference in failure modes and failure conditions.

2.3 TEST RESULTS

The comparison for the impulsive load-midspan deflection for tests within the elastic range is shown in FIG.4(a). The shapes of both the calculation and experiment is roughly the same but there is a large difference in the amount of deflection. The calculation gives quite a reasonable prediction as initial stiffness during impulsive loading can de expected to increase. Besides that, the negative value for deflection can be explained by vibrational effects of the slab. On the other hand, the experimental results shows a roughly proportional increase between impulsive load and deflection which is not normal in this case. This phenomenon can be attributed to the support conditions as the slabs had to be bolted to the supporting frame to prevent the slabs from "lifting-off" the supports during impulsive loading.

FIG.4(b) shows the comparison between the calculation and experimental values for the impulsive load-midspan deflection curves. Both the curves for D-2 was found to be quite similar while for D-1, there is a slight difference between the calculated values and the experiment towards the failure region. It should be noted that D-1 had a



(a) In elastic (b) Until failure

FIG.4 Impulsive load - midspan deflection relations faster loading rate and also a failure energy larger than D-2. An increase in initial stiffness can be expected as the loading rate increases mainly due to the effects of inertia. From the experiments, it is clear that the initial stiffness for the D-1 slab is larger. This trend, which is peculiar to impulsive loading, was clearly simulated here in the analysis.

It can be concluded that the analysis gives quite a good prediction of the ultimate behaviour of RC slabs. Besides that, it can also be said that the layered finite element method is applicable for slabs made up of different materials.

2.4 EFFECT OF MATERIAL PROPERTIES ON ANALYSIS

The effect of different materials on the behaviour of RC slabs was studied analytically. Analysis for three types of slabs, that is the reinforced concrete (RC) slab, steel fibre reinforced concrete (SFRC) slab and the test slab (a combination of RC layer and SFRC layer), were carried out. The impulsive load-midspan deflection curves are shown in FIG.5. The loading rate for all three slabs were the same. The SFRC slab is the most efficient of the three types under impulsive loading. Not only an increase in failure load can be expected but also the amount of deflection (deflection capability) is higher. This can be considered as an increase in energy dissipation in the SFRC slab. The RC slab fails at quite a small failure load without much deflection. Increase in ductility in the SFRC slab proves to be of much improvement to impact resistance.

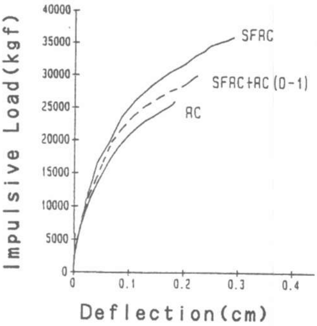


FIG.5 Impulsive load - midspan deflection curves for different materials

3. EVALUATION OF IMPACT RESISTANCE

A method of evaluation for impact resistance is of utmost necessity in dealing with the design of structures capable of withstanding impulsive loads. The definitions concerning impact resistance is still very vague at the moment. In this study, a method of evaluating impact resistance will be proposed with the hope of further applications to the field of design. Three indexes based on calculations performed will be considered here, that is:
(1) Impact load at failure (2) Deflection at failure (3) Total energy.
Four different types of concrete slabs are considered here, namely normal strength reinforced concrete (RC) slab, light weight reinforced concrete (LRC) slab, steel fibre reinforced concrete (SFRC) slab and high strength reinforced concrete (HRC) slab using the method of analysis mentioned in Section 2.1. Different material characteristics and impulsive load-time functions are applied to the analysis to study the ultimate behaviour of the slabs at

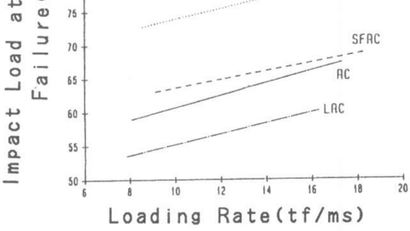


FIG.6 Effects of loading rate on impact load at failure

failure. Failure is defined here as either the crushing of concrete on the compression side (strain exceeding the ultimate compressive limit of 3500μ) or the yielding of steel reinforcement. The effects of loading rates on the indexes are also studied and linearly approximated values are shown in FIGS.6-8. Besides that, results from a series of tests carried out previously [5] will also be used to study the effects of failure modes on slabs of three different materials.

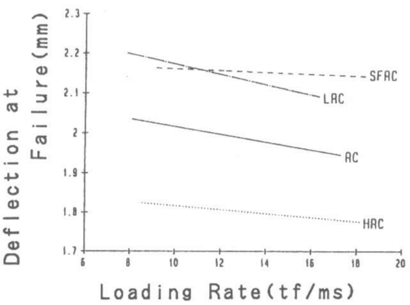


FIG.7 Effects of loading rate on deflection at failure

FIG.6 shows the impact load at failure-loading rate relation. Under an increasing loading rate, the impact force at failure shows an increase mainly because of inertia. This phenomenon can be noticed clearly in FIG.6. The HRC slab shows a large impact force at failure when compared to the other slabs, with an increase of about 20% compared to the RC slab. Not much difference is seen in the RC and SFRC slabs, but the LRC slab shows a low failure load on the whole (about -10% compared to RC).

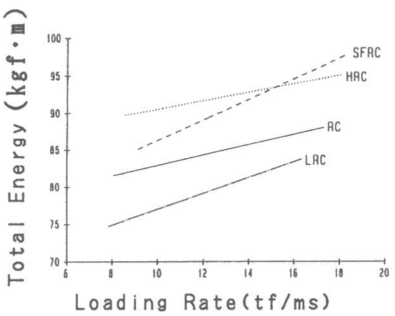


FIG.8 Effects of loading rate on total energy

FIG.7 shows the relation between loading rate and mid-span deflection at failure. It can be considered as a rough estimate of the deformation capability of the slabs. A decrease in deformation is noticed as the loading rate increases. The decrease or drop in deformation capability is quite small in the SFRC slab, having almost a stable value throughout. The LRC slab shows a large deformation capability, especially in the slow loading rate regions while the HRC slab shows small deflections on the whole.

FIG.8 shows the total energy in relation with loading rate. Since total energy is defined as the amount of energy required for slab failure under a single impact, it can be considered as a combination of the other two indexes, namely the failure load and the deformation capability. Thus, evaluations by means of this index could prove to be more effective. Total energy increases as the loading rate is increased. The SFRC slab seems to show a larger increase in index as the loading rate increases. The HRC slab shows high values in the slower loading rate regions but as the loading rate increases, the SFRC slab has a larger index value. The LRC slab shows small energy absorption properties on the whole.

TABLE 1 Failure modes for various slabs

Type of Slab	Height of Fall (cm)	Type of Failure
RC-D1	30	P.S
RC-D2	40	P.S
RC-D3	60	P.S
SFRC-D1	50	F
SFRC-D2	70	F
SFRC-D3	90	F
HRC-D1	40	P.S
HRC-D2	60	P.S
HRC-D3	80	P.S

(F:Flexural; P.S:Punching Shear)

TABLE 1 shows results of three different types of slabs under different test conditions carried out [5]. The -D1, -D2 and -D3 series of slabs represent roughly three different stages of "degree of ultimate failure" (stages 1,2 and 3 respectively in FIG.9). In other words, the results of RC-D1, SFRC-D1 and HRC-D1, for example, can be compared directly. A big change in failure mode can be noticed with the introduction of steel fibre as

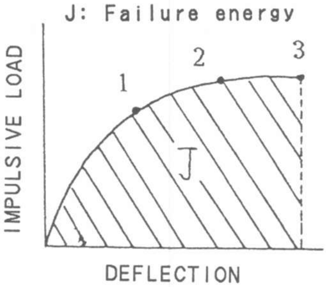
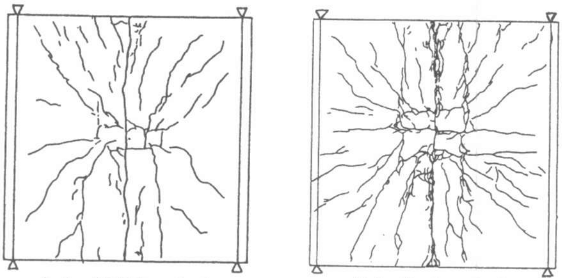


FIG.9 Definition of failure energy



(a) SFRC slab (b) D-1 slab

FIG.10 Crack pattern at failure

shown in TABLE 1. Flexural failure occurs in the SFRC slabs as compared to the other slabs which concede to punching shear. Another advantage of the SFRC slab is its ability to prevent scabbing and also reduction of cracks. This phenomena was confirmed in all the tests. FIG.10 shows a comparison of the crack pattern at the rear face of a normal SFRC slab and a tested slab as explained in Section 2.2 (a combination of RC and SFRC). It is clear that addition of steel fibre at the rear face causes the crack pattern to be the same as a normal SFRC slab and the failure mode changes to flexural failure. The amount of scabbing is also remarkably reduced when compared to RC slabs. Therefore, addition of steel fibre at the rear face can be considered to be effective for slabs under impulsive loads.

4. CONCLUSIONS

The results from this study can be summed up as follows:

(1) The layered finite element method can simulate results obtained from experiments to a good degree of accuracy. Besides that, this method is applicable to slabs with different layers of materials.

(2) An evaluation on impact resistance for slabs can be carried out based on impact load at failure, deflection at failure and also total energy.

(3) Addition of steel fibre is efficient in impact resisting structures. It causes an increase in ductility in slabs. Besides that, flexural failure can be anticipated instead of punching shear. Partial addition of steel fibre in the rear face can also change the failure mode and improve impact resisting performance.

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