論 文

[2177] MODELING OF IMPACT LOAD CHARACTERISTICS AND ITS APPLICATION TO ANALYSIS OF RC SLAB STRUCTURES

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1. INTRODUCTION

The impact force-time function and its pertaining characteristics for an impact collision are necessary not only for design of structures subjected to impulsive loads (design impact loads) but also to understand the overall dynamic behavior. The impact load characteristics (impact force-time curve, maximum impact force, duration of impact force, loading rate, impact force-time curve shape) of a deformable impacting body are simulated using a multi-mass model and then verified by experiments. Furthermore, evaluation of the resulting impact load characteristics are carried out on the effects of eccentricity in the impacting body and collision speed. Nonlinear dynamic response of RC slab structures are firstly considered by applying the impact load characteristics obtained from the multi-mass model to the layered finite element analysis (FEM). Secondly, a global method of analysis for the same impact phenomenon is considered by linking up both the analytical procedures.

2. MODELING OF IMPACT LOAD CHARACTERISTICS

A method of simulating the impact load characteristics acting on concrete structures during accidental collision of vehicle, aircraft, ship, etc. is considered. The scope of this paper is limited only to soft impacts[1] where the impacting body is considered to be highly deformable. Verification tests are also carried out to validate the analytical results.

2.1 ANALYTICAL MODEL [2]

The impacting body (deformable as in soft impacts) is modeled as a system consisting of lumped masses interconnected by nonlinear axial and rotational springs as shown in Fig.1. Each lumped mass has the longitudinal and rotational degrees-of-freedom in order to simulate eccentricity in the impacting body. The effects of eccentricity in the impacting body are considered to be of significance because the mass distribution in automobiles are not uniaxial and in most cases, collisions occur at different angles.

To simulate impact collisions into RC slab structures (deformable targets), it is considered that the concrete target is connected to a rigid

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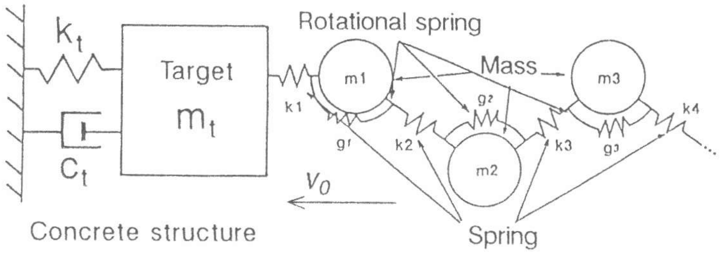


Fig.1 Multi-mass model for impact collision

wall with a spring (spring stiffness, k_T) and a dashpot (coefficient of viscous damping, c_T). By substituting the values of k_T and c_T, it is possible to simulate the deformation and also the failure process of the concrete structure up to a certain degree.

The impact force-time function during an impact collision can be given as a sum of forces in the spring next to the target and the total relative deceleration of the particular mass point[3]. Therefore, the impact force-time function acting on the target can be expressed as,

$$F(t_1) = R_1 + I_1/\Delta t_1 \qquad \cdots\cdots\cdots\cdots (1)$$

where,

R_1 = force in the spring k_1 which is located next to the target,
I_1 = impulse from collision of the 1st mass to target,
Δt_1 = time when transfer of momentum occurs.

Since the scope of this study is limited only to soft impact problems, it is considered that the second term in Eq.(1) can be neglected. Thus, the impact load function can be assumed as,

$$F(t_1) = R_1 = k_1 \cdot (u_1(t_1) - u_T(t_1)) \qquad \cdots\cdots\cdots\cdots (2)$$

where,

k_1 = spring stiffness of spring attached to the 1st mass,
u_1 = displacement of the 1st mass,
u_T = displacement of target.

The dynamic equation of motion is solved using the Newmark-β method (β=1/4). Multi-linear uniaxial material characteristics are applied in modeling the characteristics of each spring unit.

2.2 VERIFICATION BY TESTS

Verification tests are carried out to check the applicability and accuracy of the analysis. Fig.2 shows the test apparatus for impact force simulation. The impacting body is made up of 3 separate cubic metal rigid bodies (approx. 15x15x15cm cube; 25kgf weight each) connected by rubber pads (7.5x7.5x6.0cm) which act as springs. Different combinations of other mass compositions are also carried out but are out of the scope of this paper. A 200kgf weight, with a load cell attached to the front face, is used as the target. Both the target and the impacting body are suspended from the ceiling by metallic wires and can move freely in the motion similar to a pendulum. By raising both the target and the impacting body to different heights, different collision speeds can be attained. The impact force at the impacting face and acceleration response at the center of gravity (CG) of each lumped mass are recorded using an analog data recorder. Details of the test apparatus and the impacting body are given in Reference [2].

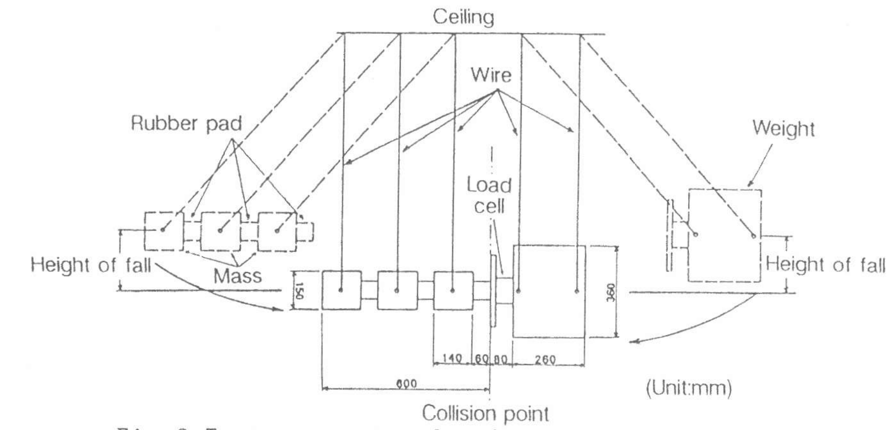
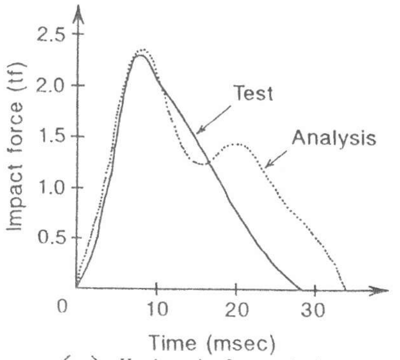
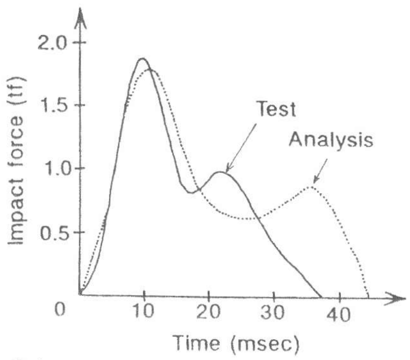


Fig.2 Test apparatus for impact force simulation



(a) Uniaxial model



(b) Model with eccentricity

Fig.3 Comparison of impact force for different models

The impact force-time curve for a uniaxial system (CGs' of all 3 masses are on the same horizontal axis) and a system with eccentricity at the middle mass (CG of middle mass is 37.6mm above horizontal axis of total system) are shown in Fig.3 (a),(b). Both results show that the analysis gives good predictions of the resulting impact forces until the first peak. But the analytical results after the maximum impact force differ from the test results. The curve shape during unloading is roughly similar in the test and the analysis in Fig.3(b). On the whole, the analysis predicts a slightly larger duration of impact force. The main reason is that the loading and unloading processes in the rubber pads (springs) are different because of viscous damping. This can be seen in the acceleration response-time relation of the 1st mass (front mass) of the axial model which is shown in Fig.4. The acceleration response in the analysis is larger than the test on the whole, with a larger period and also smaller amount of decay.

3. APPLICATION TO ANALYSIS OF RC SLAB STRUCTURES

3.1 DYNAMIC ANALYSIS OF RC SLAB STRUCTURES [4,5]

A nonlinear dynamic analysis procedure using the layered FEM is employed in the analysis of RC slab structures. The Newmark-β method is employed to solve the equations of motion during discrete time intervals while a multiaxial failure criterion proposed by Ottosen[6] is applied for concrete. The effects of plasticity, cracking in concrete elements, multi-axial yield criterion, transverse shear stresses and loading and unloading phenomena are incorporated into the analysis.

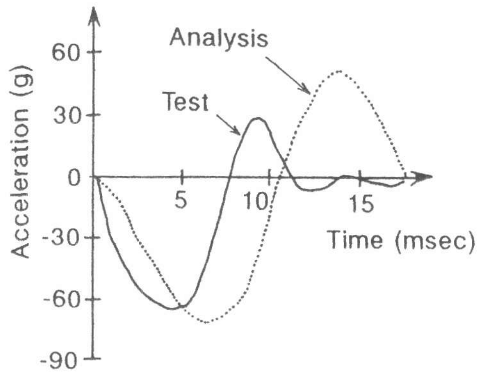


Fig.4 Comparison of acceleration response for front mass in axial model

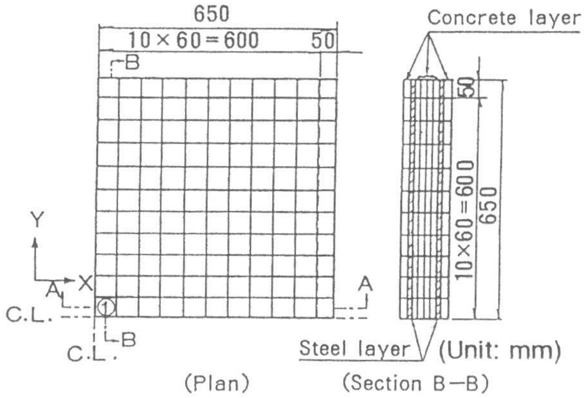


Fig.5 Layered finite element meshes for RC slab (1/4 portion)

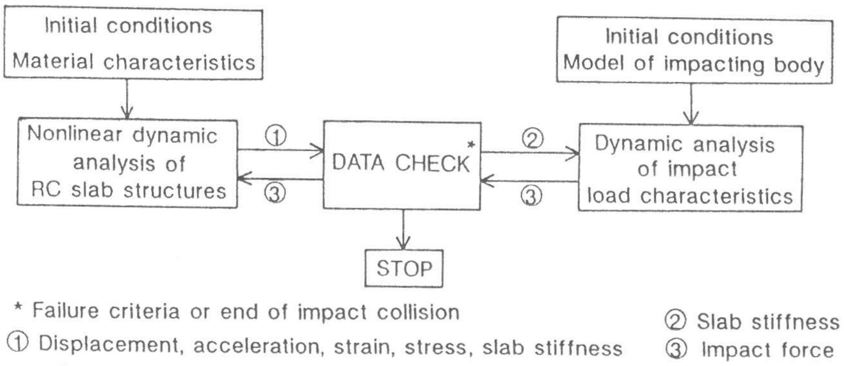


Fig.6 Linking (interfacing) procedure for global analysis of impact collision

RC slabs with doubly reinforced sections are modeled as shown in Fig.5. The slabs are divided into 8 hypothetical layers, 6 of concrete and 2 of reinforcement. The impact force is assumed to be equally loaded at the center of the slab at element ① in Fig.5. Details of the analytical procedure are supplied in Reference [4,5].

3.2 LINKING OF ANALYSES

Linking (interfacing) the multi-mass model with the dynamic analysis of RC slab structures is necessary to give a global dynamic response of the whole impact phenomenon. An outline of the procedure employed is shown in Fig.6. Applying the impact load characteristics obtained from a separate analysis into the FEM procedure would only give a rough idea of the dynamic behaviors of RC slabs subjected to impact loads. It is necessary to check the accuracy of such a procedure as a separate analysis could result in impact loads that are too large because the real failure process of RC slabs cannot be totally represented by spring constant k_T and coefficient of viscous damping c_T used in the multi-mass model.

Fig.7 shows the impact load-midspan deflection curves for the linked analysis along with the separate analysis. The impacting body consists of a 3 mass system with weight distribution of 300-400-10kgf and spring stiffness distribution of 2000-1000-2000kgf/cm. The collision speed is set at 10m/sec. From Fig.7, it is clear that not much difference can be seen in the curves using both procedures. Other behaviors at ultimate states such as distribution

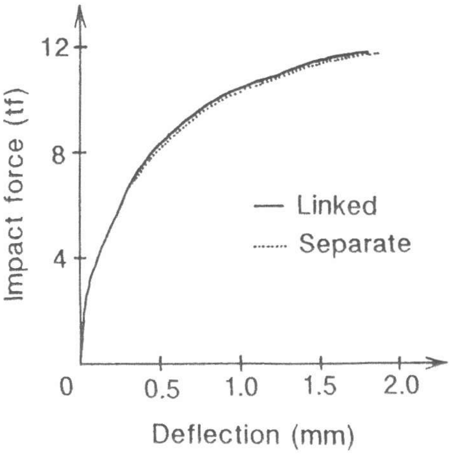


Fig.7 Impact force - midspan deflection curves for linked and separate analysis

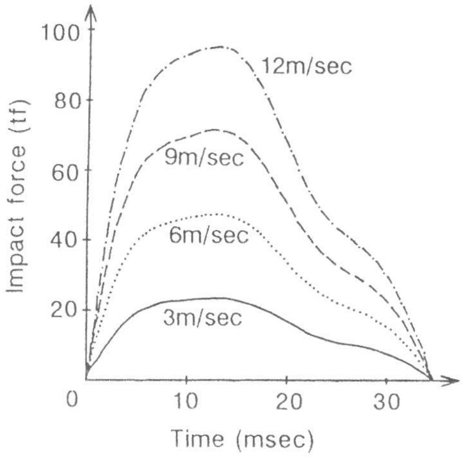


Fig.8 Impact force - time curves for different collision speeds

of deflection, crack pattern, reinforcement yielding load, etc. are also confirmed to be similar in both procedures. Therefore, it can be concluded that under soft impulsive loadings, the separate analysis produces results of adequate high accuracy in the behavior of RC slabs and thus, quantitative evaluation of the impact load characteristics using the multi-mass model is effective. But when a detailed study of the behavior of impact phenomenon is required, linking both procedures are considered to be essential.

3.3 ANALYSIS OF RC SLAB STRUCTURES

The effects of collision speeds of the multi-mass model to RC slabs are considered. Fig.8 shows the impact force-time curve for a impacting body with weight distribution of 500-200-300kgf and spring stiffness distribution of 20000-10000-18000kgf/cm. Relatively large spring stiffnesses are employed here in order to reduce the duration of impact force and subsequently the total time required for analysis.

Fig.9 shows the resulting impact force-deflection curve for the results from Fig.8. From Fig.8, it is clear that the loading rate increases as the collision speed increases. Consequently, from Fig.9, the deflection at failure decreases while the impact force at failure increases with the increase of loading rate. These results are in agreement with the general impact phenomena. Fig.10 shows the distribution of deflection at failure (transverse and longitudinal directions) for the 4 different collision speeds. Deflection is spread at an equal ratio throughout the cross sections especially for the lower collision speeds. As the collision speed increases, the deflection at failure is dominant near the mid-span. Therefore, at higher collision speeds, local failure becomes more dominant.

4. CONCLUSIONS

The main conclusions from this study can be summed up as follows:

(1) The impact load characteristics for soft impulsive collisions by deformable bodies into concrete structures can be roughly simulated using the multi-mass model, which consists of lumped masses interconnected by axial and rotational springs. In particular, the impact force until the first peak can

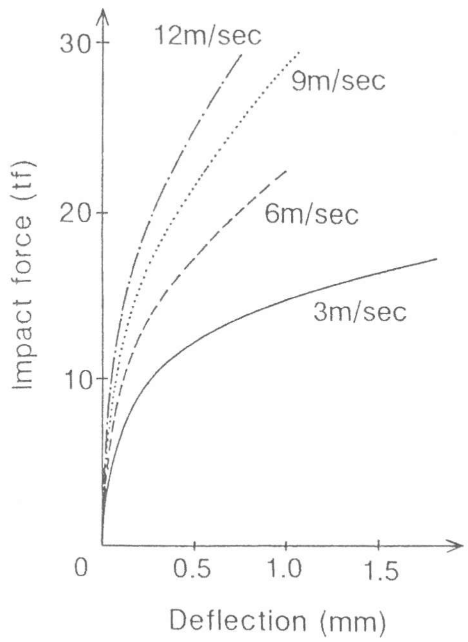
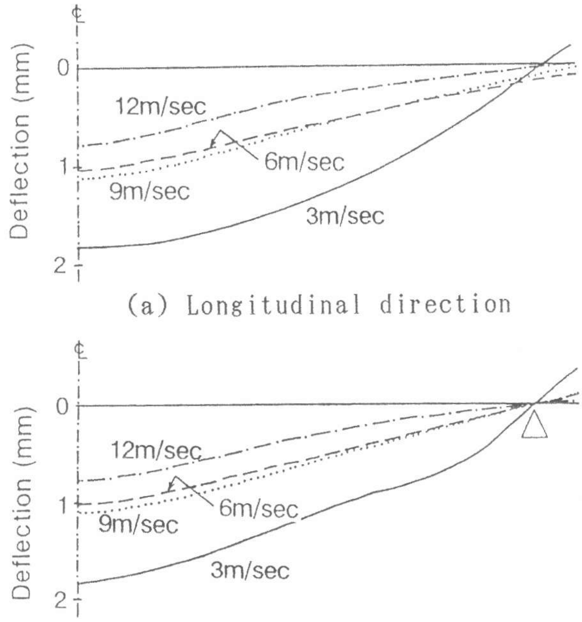


Fig.9 Impact force-midspan deflection curves for different collision speeds



(b) Transverse direction

Fig.10 Distribution of deflection for different collision speeds

be effectively simulated.

(2) A global analytical method for the analysis of dynamic response of concrete structures subjected to soft impacts from deformable bodies can be attained by linking the proposed analysis of impact load characteristics with the nonlinear dynamic analysis of RC slab structures.

(3) An increase in collision speed during impact collisions causes the deflection in RC slab structures to concentrate around the mid-span, thus causing local failure to be more dominant.

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