DYNAMIC FRACTURE OF CONCRETE STRUCTURES DUE TO SEVERE EARTHQUAKES AND SOME CONSIDERATION ON COUNTERMEASURES

Jin-ichi Takeda (I)

SUMMARY

This paper deals with the contribution of the effects of loading speed on the brittle shear fracture of concrete or reinforced concrete structures during severe earthquakes. In high rate shear tests of concrete specimens with or without reinforcement, the fracture of specimens occurred suddenly at the extremely small shear displacement compared with the value in static tests, and this brittle shear fracture was materialized by rapid extention of shear cracks. The high rate loading tests on bond stress also reported. Some countermeasures for the occurrence of brittle shear fracture of concrete or reinforced concrete structures are considered.

INTRODUCTION

Many brittle fractures and tragic damages of concrete or reinforced concrete structures have frequently brought on in severe earthquakes. These brittle fractures still remain as one of the most important problems in earthquake resistant design of structures.

This paper deals with the contribution of the effects of loading speed on these brittle fractures of concrete or reinforced concrete structures during severe earthquakes. Hitherto the effects of loading rate on responses of structures usually have not been considered in structural design, because there were little data on it. It is well known, however, that the mechanical properties of concrete (Ref. 1), reinforcement (Ref. 2) and the bond action between concrete and reinforcement (Ref. 9) varies widely with the rate of stressing (and straining) concern. The author has studied on the dynamic deformation and fracture of concrete and reinforced concrete structures and structural members encountered with impact or blast shock, which might be regarded as higher rate loading than any earthquakes. The study was carried out experimentally with the various loading rates ranging from the rate in static test to that in impact or blast shock, because this study was intended to know the variation of dynamic responses of the structures with the increment of loading rate, in the range of loading rate concern. This comes from the idea that the key of design method of structures for resisting impact, etc. is to know what changes are imperative from static structural design. It is considered that the results of the study on dynamic responses of structures during earthquakes is presumably contained in the results of these studies, because the range of loading rate of these studies would generally contain the loading rate of earthquakes.

In order to know the rate effects on structural materials, members or structures during earthquakes, if some experiments are carried out with the loading rate only slightly larger than that in static test, then the distinguished effects of loading rate would not be obtained, because the inevitable

(I) Professor of Structural Mechanics, Kumamoto Institute of Technology, Japan

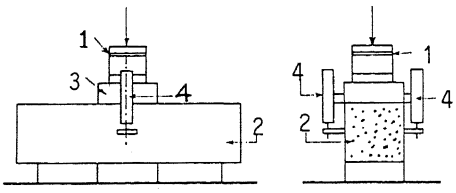
errors concerning experiments can not be divided from the effects of loading rate.

In the experiments conducted in the past (Ref. 1 and 2) on the effects of loading rate with compressive and tensile loads on concrete and with tensile load on reinforcements, any unfavorable tendency for structural design is not obtained. That is, both the stress at some strain and the strain at the maximum stress in these tests usually take larger values in high rate loading tests than in static tests. In the case of shearing tests on concrete specimens with and without reinforcement, however, the tendency inversely changes, and unfavorable tendency appears. The shearing displacement at the maximum stress in the tests drastically decreases and the sudden and violent fracture of the specimens occures in the case of larger displacement rate than about 2 cm/sec. It is considered that this tendency might be materialized by quick propagation of cracks throughout whole section of the specimens which initiated at the edges near to loading apparatus in the tests.

What must be studied is that if the loading rates (or displacement rates) of shear deformation of concrete or reinforced concrete structures during earthquakes are in the range of loading rate which makes the unfavorable shear fracture mentioned above. This paper discussed on this problem.

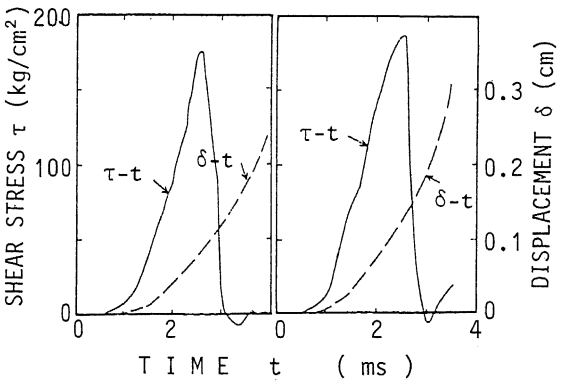
RATE EFFECTS ON CONCRETE AND REINFORCED CONCRETE PRISMS IN SHEAR TYPE LOADING

Specimens which were used in high rate shearing tests are concrete and mortar prisms 15cmx15cmx50cm in dimension with and without reinforcement (SD-35, D10). The tests were carried out in three kinds of displacement rate; static loading test (notation S, mean displacementrate of 1.26×10^{-3}cm/sec), medium rate loading test (III,1.1 cm/sec) and high rate loading test (I, 50.4 cm/sec);with shearing apparatus (Fig. 1) set in high rate testing machine designed by the author. Concrete and mortar used are of water-cement ratio of 0.5 and the average of compressive strengths are 411 kg/



1: Load Cell, 2: Loading Head
3: Specimen (15cmx15cmx50cm)
4: Potentiometer

Fig. 1 Set-up of shear tests of concrete and mortar specimens, with or without reinforcement.



Mortar, displacement rate=41.5cm/s

Mortar, with reinforcement,displacement rate=62.0cm/s

Fig. 2. Shear stress-time and displacement-time diagrams in high rate shear tests.

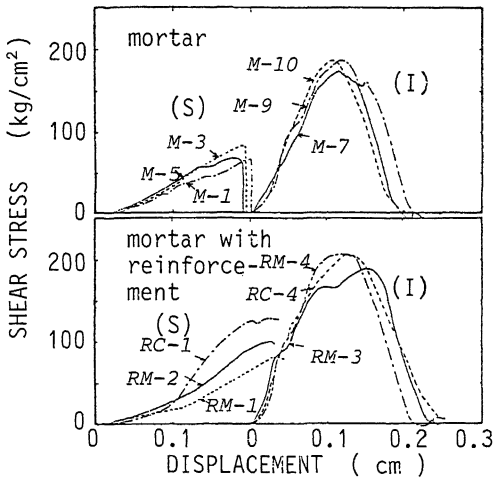


Fig. 3. Comparison of shear stress= displacement diagrams in static shear test (notation (S)) with that in high rate shear test (I).

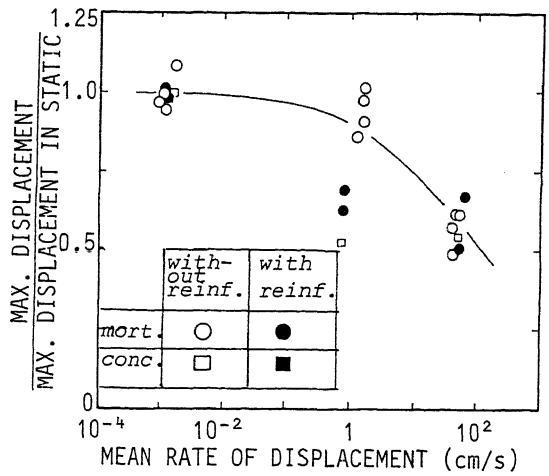


Fig. 4. Change of maximum displacement with the mean rate of displacement of loading head in shear tests.

cm^2 in concrete and 438 kg/cm^2 in mortar. In the tests, shear stress and displacement were measured with measuring system of wide frequency range (0 - 100 KHz).
Examples of shear stress-time and displacement-time diagrams which have been obtained in the tests are shown in Fig. 2 and examples of shear stress-displacement diagrams are shown in Fig. 3. It is seen that the displacement at the maximum shear stress on stress-strain diagrams in Fig. 3 takes extremely small value in high rate loading tests (rate notation (I), Fig.4), though the maximum shear stress usually increases with the increment of loading rate. Absorbed energy until stress reaches the maximum shear stress does not so increase with the increment of loading rate as the maximum shear stress does (Fig. 5).

On shear stress-time diagrams in Fig. 2, it is noticed that the descending part of these diagrams just after the stress reaches the

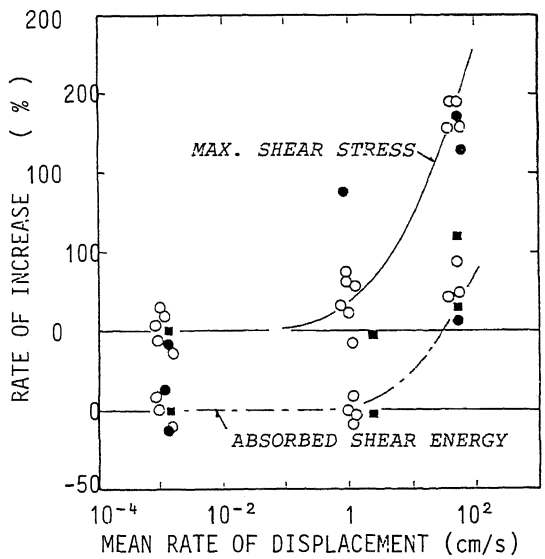


Fig. 5. Rates of increase of max. shear stress and absorbed shear energy with the mean rate of displacement.

maximum stress quickly decreases to stress zero in extraordinary short time (below 0.5 milli-sec), even in the the case of the specimen with reinforcement. And the speed of stress returning from the maximum stress to zero is far larger than the shearing speed by test apparatus (Fig. 6). The tendency that the specimen loses its resistance to shearing just after the stress reaches the maximum stress in the test, as mentioned above, is seen not only in high rate loading test, but also in medium rate and static loading test, though the speed is less in the case of smaller loading rate (Fig. 6). In static loading test, details of the process in the test can be observed directly and the cause of the above tendency is understood. That is, as shear stress increases gradually and reaches near to the maximum stress in static shear test, cracks suddenly appeared on near parts of specimen to the edges of loading head and they quickly propagated to the whole section in the direction of shear force. It is rational consideration that the same phenomena also cause in the case of both medium and high rate loading tests in shear type.

The high speed propagation of cracks in concrete was already found (Ref. 3, 4) in also high rate tensile tests of concrete plate with the initial flaw arranged beforehand in them, which was shown in Fig. 7, by the author. These tests were carried out to get dynamic fracture toughness with three kinds of loading rate ranging from the rate of static test (loading rate of about 6 kg/sec) to that of about 1.8×10^6 kg/sec. Fig. 7 shows the change of speed of crack propagation in the specimen with the increment of loading rate and also shows that the speed of crack propagation attains about 1000 m/sec in high rate loading test. In these tests, the curved running of cracks, which has been theoretically indicat-

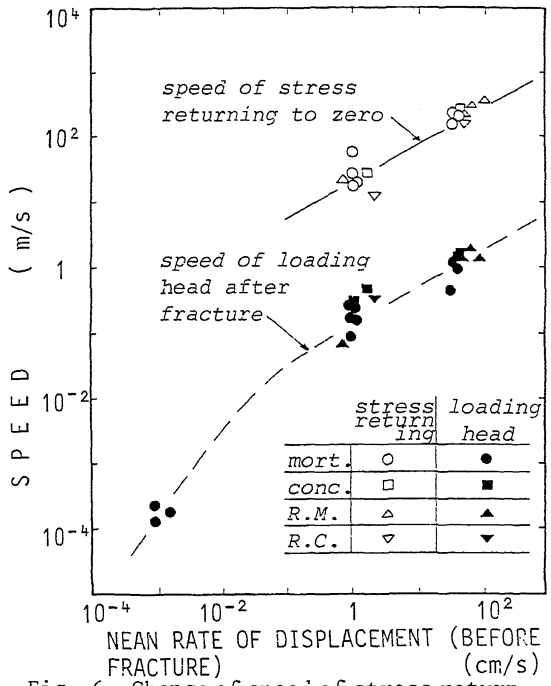


Fig. 6. Change of speed of stress returning to zero and of loading head after fracture in shear tests with the increment of mean rate of displacement.

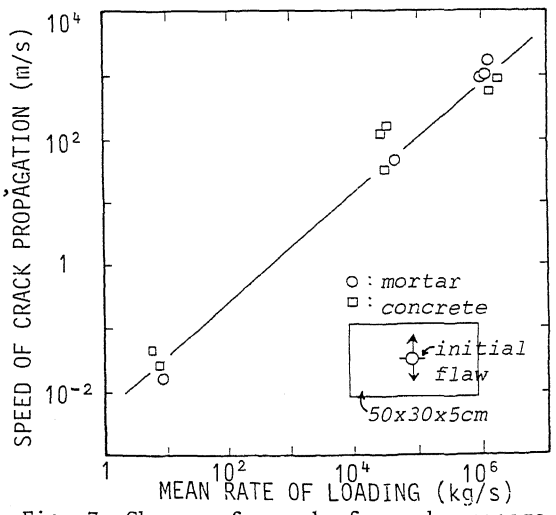
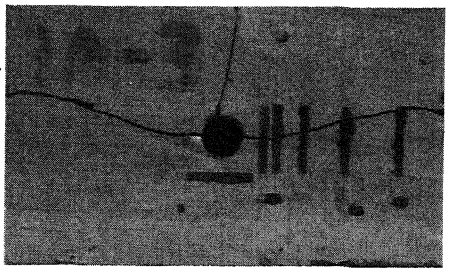


Fig. 7. Change of speed of crack propagation with the increment of mean rate of loading in tensile tests of mortar and concrete plates with initial flaw.

ed beforehand by E. H. Yoffe (Ref. 5) that it will occur in only high rate propagation of cracks, was also found in the case of highest rate loading tests carried out (Phot.1). Therefore, it can be concluded that the high rate propagation of cracks in the shear tests of concrete prisms, mentioned above, is fully supported also by the theory.



Phot.1. High speed running of cracks in mortar plate.

From Fig. 4, 5 and 6, it is realized that the same phenomenon as the above in the concrete specimens also occurs in the specimens with reinforcement. This shows that the reinforcement set in concrete, in the nearly extent to reinforcement of specimens tested, does not have power to stop the cracks extending in concrete and therefore it can not work as a crack arrest. These understandings are realized in also bending (Ref. 6) or shear tests of reinforced concrete beams (Ref. 7) in which many cracks extended across the reinforcements placed in specimens were observed. This property might be materialized by the difference of character between concrete and reinforcement that the former makes cracks within extremely small strain ($1\text{-}2\times10^{-4}$ of strain) occurred across the location of cracks, though quite an extent of strain is needed to get the effects of the deformation of the latter because the strain of the latter is driven by bond stress. Theoretical analysis on stress waves in a medium with the inclusion of rigid circular cylinder in it also gives the result that the propagation of stress waves is not affected by the circular rigid inclusion (Ref. 8).

It is fully reasonable that the fast running of shear cracks, mentioned above, presumably occurs in all loading rates ranging above that in medium loading rate, though the shear tests on concrete and mortar prisms were carrid out with discrete loading rates.

OTHER RATE EFFECTS RELATED TO DYNAMIC STRUCTURAL DESIGN

One of the other rate effects demand deliberation to the earthquake-resistant design of reinforced concrete structures is the rate effect on bond stress. The pull out tests in high rate loading of reinforcement set in concrete prisms (10cmx10cmx10-40cm) were carried out (Ref. 9). The reinforcements of SD35, D-10 or SR24, 9ϕ was placed on the axis of the concrete prisms with prescribed bonded length of 5-40cm. Specimens were tested in the age of concrete of 3-3.5 months with high rate testing machine in three kinds of pull out rate; static rate (notation (S), pull out rate of $2\text{-}5\times10^{-3}$cm/s), medium rate ((Ⅲ), 2-5cm/s) and high rate ((I), 2-5x10 cm/s). Pull out load, strains at several points on the reinforcement and slip deformation of reinforcement from the concrete prism were measured with measuring system of wide frequency range (0-100KHz).

On the distribution of bond stress on reinforcements, the clear difference between deformed reinforcement and plane reinforcement set in the specimens was found in these tests. In the case of deformed reinforcement, the distributing extent of bond stress on reinforcement is substantially constant (approximately ten times of diameter of reinforcement in 40cm of bond length) throughout the test, though the bond stress increases with the increment of applied load until the reinforcement is broken at last in it's outer part of concrete at the maxi-

mum applied load (Fig. 8 and 9). On the contrary in the case of plane reinforcement, the distributing extent of bond stress gradually extend with the increment of applied load (Fig. 9). These tendencies on the distribution of bond stress are also seen in the tests of all loadingrate, except in the case of static test on deformed reinforcement which shows somewhat different tendency (Fig. 9), though the maximum bond stress takes larger value in the test done with larger loading rate on same kind specimens (Ref. 9).

From the tendency of bond stress distribution on deformed reinforcement, mentioned above, it is apprehended that the deformed reinforcements in reinforced concrete structures likely to make larger deformation or break down of them by the large deformation of structures or structural members, because the larger stress of reinforcements transmitted by bond stress which concentrates at certain points within the largely deformed portion of the structural members can not but infinitely increase up to break down of reinforcements, especially in the case of higher rate loading.

In other rate effects related to dynamic structural design of reinforced concrete structures, there is a change of

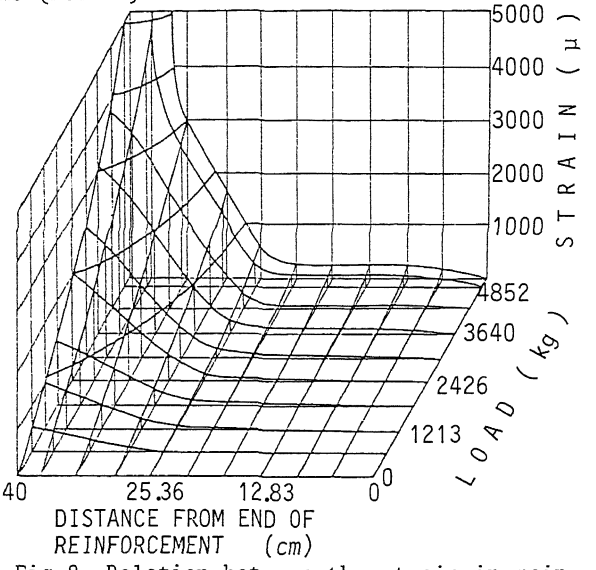
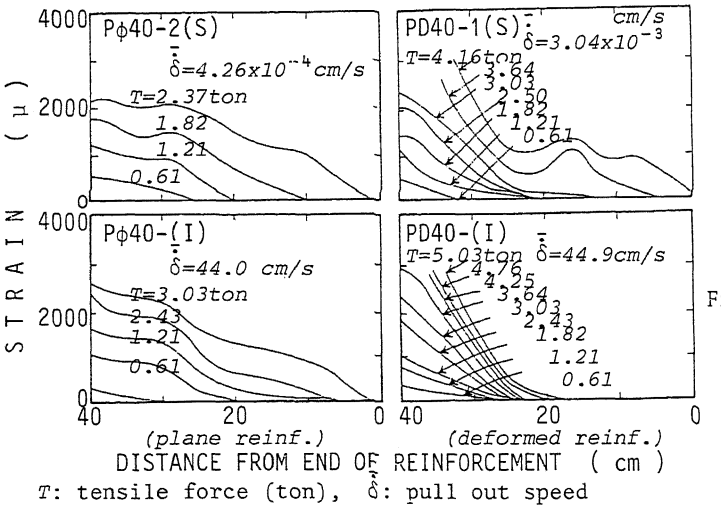


Fig.8. Relation between the strain in reinforcement (SD35,10D),load and distance from the end of reinforcement in bond test done with high rate loading (speed=44.9cm/s).



T: tensile force (ton), $\dot{\delta}$: pull out speed

Fig.9. Comparison of bond stress distribution on reinforcements between those in the cases of deformed and plane reinforcements, and static and high rate loading test.

tensile stress-strain diagram of reinforcements by the loading rate concern in which the stress drastically decreases from the yield stress just after the stress reaches the yield stress in high rate tensile test of reinforcements (Ref. 9), with which violent vibrations might be caused on the reinforced concrete structural members, as if attacked by impact.

The rate effect in shear test of reinforcement itself (Ref. 10), which indicates the same tendencies as in the case of concrete and reinforced concrete prisms, might have concern rather with steel construction.

INFLUENCES OF LOADING RATE ON FRACTURE OF REINFORCED CONCRETE STRUCTURES AND SOME COUNTERMEASURE

It is reported in preceeding chapter that the displacement at which the shear fracture of concrete occurs, greatly decreases compared with the values in static loading and the small cracks generated at loaded area quickly propagate to the whole section in high rate shear tests on concrete prisms. This tendency is also seen in medium rate loading test (mean displacement rate of 1.1 cm/s) and high rate loading test (mean displacement rate of 50.4 cm/s) carried out. Therefore, in the loading conditions to some members of concrete structures in which the rate of shear deformation is greater than 2 cm/s, there arises fear of damage by the violent brittle fracture of concrete in structural members. And it is extremely noticeable that the reinforcements in those members probably don't work to resist the above crack extention.

On the velocity response spectrum based on the data of big earthquakes in the past, many reports showed that the velocity response in the range of natural period over about 0.3 sec takes larger value than 10 cm/sec in many cases. Accordingly, it is duly considered that the relative displacement of upper parts of columns or walls to lower parts is frequently materialized with the velocity over 10 cm/sec in the case of low rise buildings attacked by severe earthquakes, and if the columns or walls do not have sufficient strength or already have some cracks, then the tragic dynamic shear fracture of columns or walls might be brought about instantaneously by high rate propagation of shear cracks to whole the section of the columns or walls. Addition to this, the bond stress distributing on deformed reinforcements in the structural members, which concentrate to some portions under large deformation and infinitely increase up to the break down of reinforcements with the increment of applied load accompanying with growing deformation, mentioned previously, might cooperate with the dynamic shear fracture of reinforced concrete structures during severe earthquakes.

Two measures are given to counter the violent dynamic shear fracture of concrete or reinforced concrete structures; first is to restrain the occurrence of cracks in the area under large shear stress which quickly propagate to the whole section of members of the structures applied by high rate shear force, second is to decrease the velocity of shear displacement of columns or walls for the reduction of rate effects on the shear fracture of them.

As the first measure, following procedures are considerable;

(1) reduce the shear stress of columns or walls, by, for example, adding sectional area of these members at dangerous parts,
(2) at the connections of structural members, for examples, beams and columns, wall girders and columns, etc., use haunchs or corbels to eliminate the sharp changing of sectional area at the connections, in order to avoid the occurrence of initial cracks,

(3) remove the uneven parts or dents close to points of connections of members which are ready to occur initial cracks by loaded shear force.

One of the second measures is to reduce the responses of structures during earthquakes by arranging proper rigidities of the members. It is clear,however, that only the use of a lot of reinforcements is not always effective for getting large rigidity or effective sectional areas of structural members or structures.

These countermeasures are practically not so new for structural design of earthquake-resistant structures, however, the new meanings of them are given by this study.

CONCLUSIONS

1. In high rate shear tests of concrete prisms with or without reinforcement, the fracture of specimens occurred suddenly at the extremely small shear displacement compared with the value in static test.
2. It was understood that the brittle fracture was materialized by rapid propagation of shear cracks made in the specimen near to loaded areas.
3. The rapid propagation of shear cracks was observed in the tests done with loading rate larger than that of medium loading test (mean rate of displacement is 1.1 cm/sec), and the reinforcement set in the concrete specimens did almost not work to stop the crack propagation.
4. It was observed that the distributing extent of bond stress on deformed reinforcement was almost constant in high rate pull out tests of reinforcement set in concrete prisms, though applied load increased.
5. For the occurrence of brittle shear fracture of concrete or reinforced concrete structures, there are two countermeasures; to restrain the occurrence of initial cracks in concrete of structural members applied shear force, and to reduce the velocity of shear deformation of the structure loaded.

REFERENCES

1) J. Takeda et al.: Deformation and Fracture of Concrete Subjected to Dynamic load, Proc. of ICM-1, Kyoto, Vol. IV, pp. 267- 277, 1971
2) J. Takeda et al.: Mechanical Properties of Concretes Subjected to High Rate Loading in Compression, Tension and Bending Types (in Japanese), Trans. of AIJ, No.77,pp. 1-6, 1962
3) J. Takeda et al.: Crack Extension in Concrete by High Rate Loading (in Japanese) CAJ Reviw No.33, pp. 417-420, 1979
4) J. Takeda et al.: Mechanical Properties of Concrete and Steel in Reinforced Concrete Structures Subjected to Impact or Impulsive Loading, Proc. Interassociation Sympo. on Concrete Structures Under Impact and Impulsive Loading,Berlin,pp.83-91, 1982
5) E.H.Yoffe: The Moving Griffith Crack,Phil. Mag. pp.739-750, 1951
6) J. Takeda et al.: Deflection and Fracture of Reinforced Concrete Members Sub. to Dynamic Load, Proc. EES, pp. 69-76, 1973
7) J. Takeda et al.: Influences of High Rate Deformation on the Fracture of Str. During Severe Earthquakes, 7-ECEE,pp.23-30,1982
8) Y.H.Pao,C.C.Mow;Diffraction of Elastic Wave, Crane Russak,
9) J. Takeda et al.: (in Japanese), CAJ Reviw, No. 36, pp.466-469, 1982
10)J. Takeda et al.: (in Japanese), Annual Conv. of AIJ, 1970, pp.1009