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DETERIORATIVE RATE EFFECTS ON BRITTLE FRACTURES OF REINFORCED CONCRETE STRUCTURES DURING SEVERE EARTHQUAKES

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SUMMARY

It has been found that one of the two rate effects :the effect on fracture criterion: on concrete bring about dreadful fracture on concrete and reinforced concrete structures. This unfavorable and deteriorative rate effect was studied experimentally with Mode I and Mode II specimens in fracture mechanics. In the Mode II experiments, it is clarified that shear crack in concrete easily extend throughout the specimen in high rate loading, though it is hard to extend outstandingly in static test, and high speed extension of shear crack can not be restrained by usual reinforcements used. Photographs taken by scanning microscope was used in this study. Some countermeasures on this phenomenon during sever earthquakes are also discussed.

INTRODUCTION

Extensive brittle fracture and tragic damages have frequently brought about on concrete and reinforced concrete structures during severe earthquakes. A number of studies have been carried out, however, the complete solution of this problem has not been obtained yet.

The brittle fracture of concrete or reinforced concrete structures are caused by high speed running of cracks, which are made by strong vibrations during severe earthquakes. By the way, rapid extension of cracks in concrete breaks out also in high rate loading tests, however, cracks never extend rapidly under static loading test. Accordingly, it is considered that dreadful damages of concrete and reinforced concrete structures under severe earthquakes are made by rate effects on crack extension in concrete, namely rate effects on fracture criterion of concrete under high rate loadings.

Rapid extention of cracks, no doubt is a matter in fracture mechanics, therefore this problem should be studied on the basis of fracture mechanics, which is now being studied actively.

In this study, two kinds of specimens : Mode I and Mode II specimens: in fracture mechanics were used and crack extension tests were carried out with several loading rates. The surfaces of crack extended are studied with a scanning microscope. Some countermeasures on this problem are discussed.

RATE EFFECTS ON HIGH RATE DEFORMATION OF STRUCTURAL MATERIALS

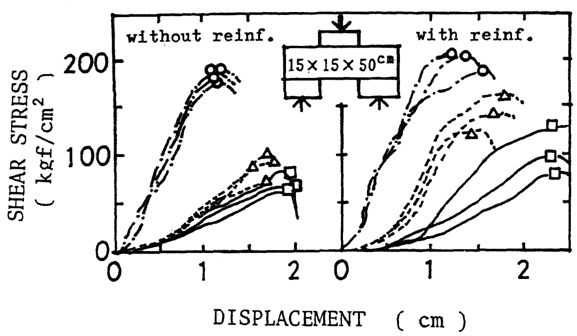
It has been hitherto vaguely considered that the responses of structures under earthquakes might not be affected by rate effects which usually occur in structural materials under high rate straining, though it is not correct. It has already been frequently reported that dangerous brittle fractures of reinforced concrete structures brought about with tremendous speed of extension and with absolutely different appearances from that in static loadings, during severe earthquakes.

The rate effects are phenomena in statistical thermodynamics which cause changes of mechanical properties of materials under high rate straining (or high rate loading), and they are divided into two effects, the effect on the relation between stress and strain and the effect on fracture criterion of the materials subjected to high rate loadings.

In the beginning, the study on first effects, which occur with the way that the stress at a certain value of strain takes larger value in high rate loading tests than in static test of structural materials in many cases, merely preceeded in connection with timely requirements to establish a standard rate of testing of structural materials.

This has led the presumption that the static relations between stress and strain of materials might be safely adopted instead of dynamic relations in order to carry out the dynamic design of structures. It has been stimulated also by the results of tests that the strain at fracture (or yield, in case of steel) of materials took larger value in higher rate loading tests than in static test with compressin, tension and bending load on concrete and steel.

On the contrary, however, there were found unfavorable effects in latter effects : effects on fracture criterion : for dynamic design of reinforced concrete structures in high rate shearing tests etc. Fig. 1 shows the relations between shear stress and displacement in shear tests on concrete prisms with or without reinforcements which carried out with several rate of displacement ranging from 10^{-3} cm/s to 1 m/s. It is seen that the shear stress at a certain displacement is larger in higher rate loading tests than in static test as mentioned above, whereas the displacement at max. shear stress is lesser in higher rate loading tests than in static test (Table 1). It is also known that the duration from the time at max. shear stress to fracture time is shorter in higher rate loading tests than in static test, this indicates that the extending speed of shear cracks is larger in higher rate loading and causes brittle fracture. Such phenomena are seen



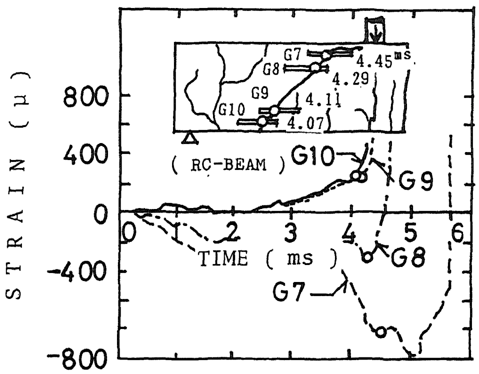
○ : high rate loading (40 ~ 100 cm/s)
△ : medium rate (0.1 ~ 0.7 cm/s)
□ : static (1 ~ 2×10^{-3} cm/s)

Fig. 1. Max. shear stress and its displacement in shear test of concrete prisms, with or without reinforcements.

Table 1. Changes of the ratios between displacement at max. shear stress D_m and that in static test D_{ms} in shear tests of mortar and concrete prisms.

LOADING RATE OF TEST	MORTAR with reinf.	MORTAR without reinf.	CONCRETE with reinf.	CONCRETE without reinf.	REINF. ITSELF
medium rate	0.87	0.75	0.75	0.73	0.96
high rate	0.58	0.64	0.60	0.63	0.83

Mean displacement rate; static:4.1×10^{-3}cm/s, medium rate:2.0 cm/s, high rate: 45 cm/s



o :time when shear crack passed on gage.

Fig. 2. Records of gages on a shear crack of reinforced concrete beam tested with impact load.

not only concrete, but also reinforced concrete and reinforcement itself, as shown in Table 1 (Ref. 1).

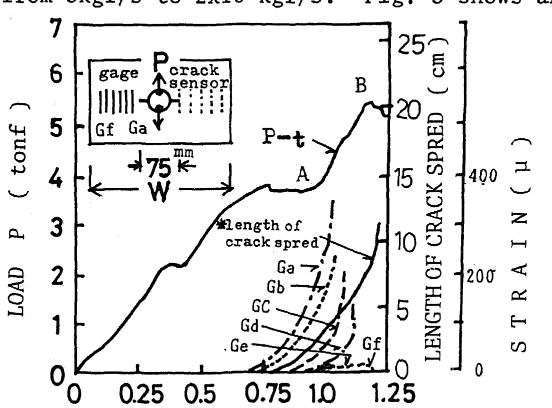
Fig. 2 shows a result of impact tests (4.6m/s of impact speed) of reinforced concrete beam (reinforcement rate of 1.2 %), in which a shear crack happend passed on gages stuck the flank of the beam. The extending speed of shear crack, measured from record of gages, is 160 m/s in average. Thus, it is certainly concluded that the brittle fracture of reinforced concrete structures or structural members caused during severe earthquakes might be materialized by rapidly extending shear cracks from inner flaws, maden in structural members inherently or by newly applied load. It should be rate effects on reinforced concrete structures caused by severe vibrations.

There are also found other unfavorable rate effects, caused in reinforced concrete structures, for example, degrading of ductility of structural members due to the rate effects on bond action between concrete and reinforcements, etc.

EXPERIMENTAL RESULTS AND DISCUSSION

In order to obtaine the rate effects on crack extension in concrete, two kinds of experiments, with Mode I and Mode II specimens in fracture mechanics, were carried out. The Mode I specimens are shown in Fig. 3 as a example, and are concrete and mortar plates of 30cm x W(50cm, 30cm, 20cm, 12cm) x 5cm(thickness) and with a initial crack of 7.5cm in length.

The specimens were applied with tensile load with the loading rate ranging from 3kgf/s to 2×10^6kgf/s. Fig. 3 shows an examlpe of the data obtained in high



* obtained from the measurements of crack sensor

Fig. 3. Example of test data of Mode I specimen, tested with high rate loading (mortar, W=50cm, loading rate= 1.44×10^6kgf/s).

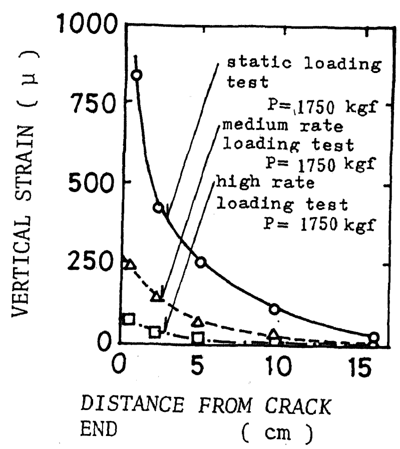


Fig. 4. Distribution of vertical strains on the line of crack, measured before crack starts to extend, in Mode I tests loaded with three kind loads.

Table 2. Fracture Toughness, obtained from Mode I test (mortar).

LOADING RATE OF TEST	MEAN LOADing RATE (kgf/s)	2 a / W		
		0.15	0.25	0.625
static	7.0	110	95	60
medium rate	4.7×10^{4}	135	120	65
high rate	1.4×10^{6}	245	220	110

unit of F. T.: $kgf\text{-}cm^{-3/2}$

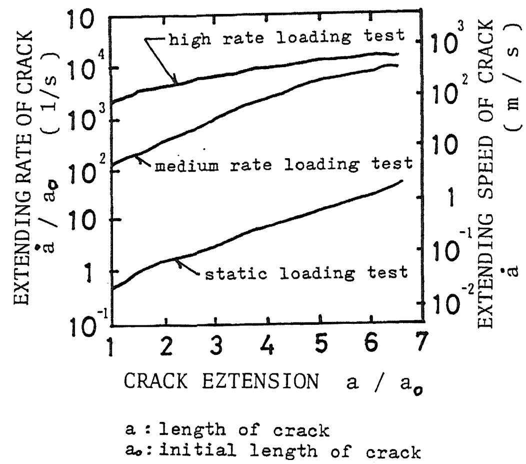


Fig. 5. Extending speed of crack versus crack extension in Mode I tests, tested with three kinds of loading.

rate loading test (the mean loading rate up to the beginning of crack extension is 3.8×10^{6}kgf/s) on mortar specimen (W=50cm). It was known that the stress distribution in the specimens tested with high rate loading has already changed from that in static test, even before crack starts to extends (Fig. 4). This figure shows the distributions of vertical stress on the line of initial crack, measured at the same magnitude of load in the tests carried out with three kinds of loading rate.

The load just before crack starts extension, namely fracture toughness, also changed with loading rate and are larger in higher rate loading tests than in static test (Table 2). therefore, in high rate loading, crack extension is restrained until load becomes larger value than in static loading, however, once crack starts to extend, the crack rapidly run with tremendous high speed of nearly 1000m/s (Fig. 5). The high speed extension of crack in high rate loading test requires so large quantity of kinetic energy that applied load should increase during crack extension, as seen in Fig. 3 (a part of AB on P-t diagram). These phenomena are observed in only the tests of high rate loading and the specimens of these tests show curved crack which has been theoretically indicated by E. H. YOFFE that

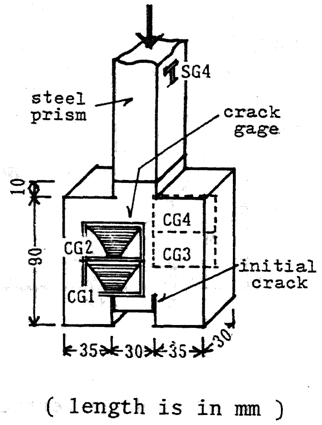


Fig. 6. Mode II specimen.

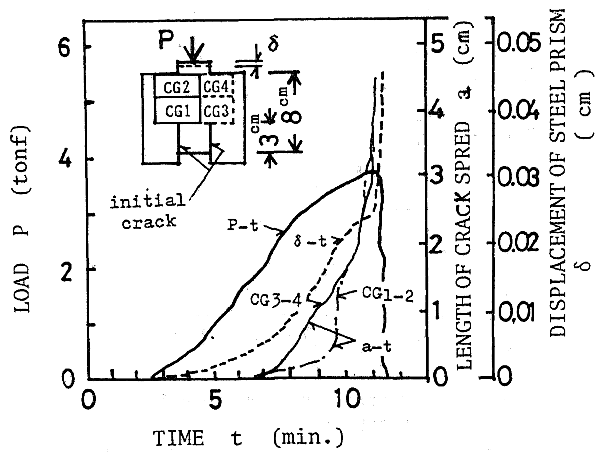


Fig. 7. Example of test data on Mode II tested with static load.

it will occur in only high rate extension of cracks (Ref. 3).

The Mode II (shear crack) specimen, made of mortar, is seen in Fig. 6. Two kind of tests, static test and impact test, are carried out, and applied load (or strain wave given, in case of impact test), deformation and crack extension with crack gages are measured in the tests.

An example of data of static tests is shown in Fig. 7. It is clear in this figure that applied load continuously increases throughout crack extension, in the same way of Mode I test done with high rate loading (Fig. 3), except the tendency on extending speed of crack. In this test, extending speed of crack is very slow and only 0.37 mm/s in average. This says that the static extension of shear crack is considerably difficult to occur and requires a large quantity of energy. The energy release rate G_F in the test, which is obtained from Fig. 8, is 2820N/m and exceedingly large. It is explained that the shear crack extended

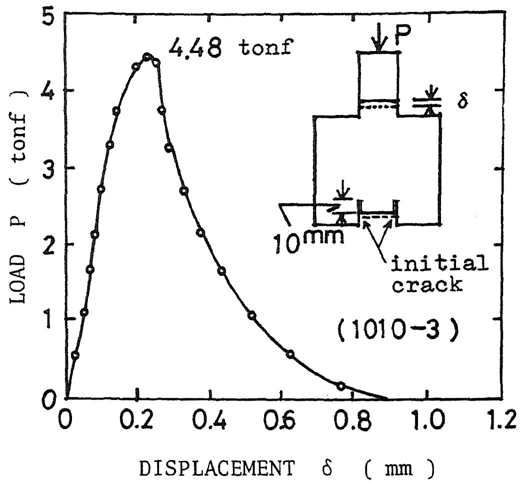
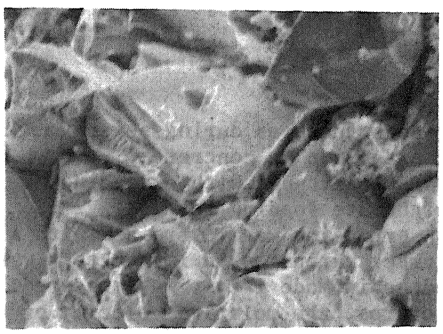
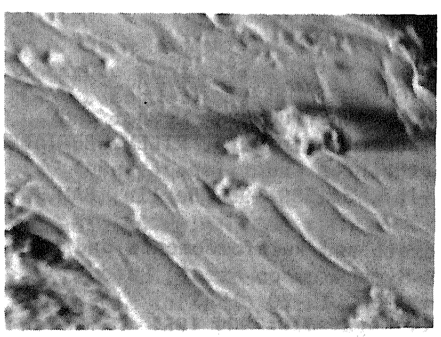


Fig. 8. Example of load - displacement curve of Mode II tests, tested with static load.



(a) static test



(b) impact test

10μm

Phot. 1. Surfaces of cracks of Mode II test (x1000)

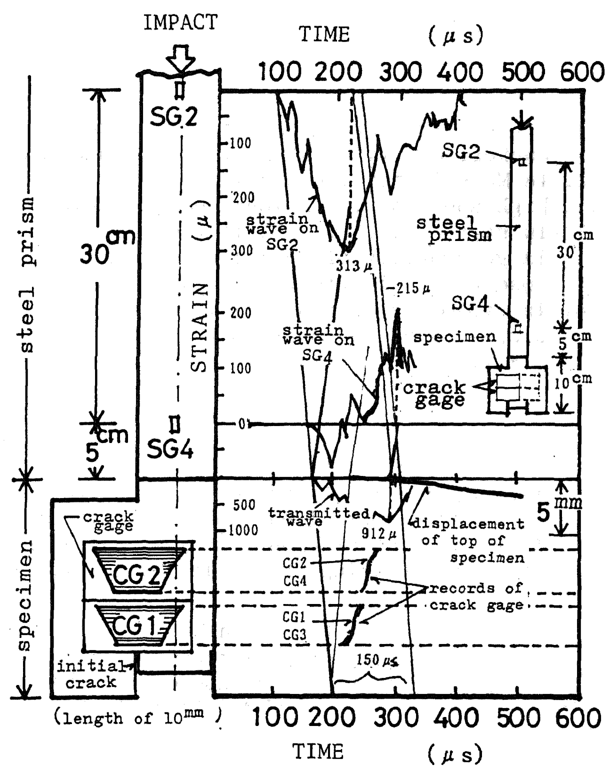


Fig. 9. Example of test data on Mode II tested with impact.

statically is very complicated, and has threedimensional geometry, as seen in Phto. 1-(a) taken with scanning microscope, and it demands a large quantity of energy.

On the contrary, impact tests of Mode II specimens showed absolutely different features from that of static tests. The top of the specimen was stuck to the end of steel prism of 3cm x 3cm x 120cm with gypsum and other end of steel prism is impacted (Fig. 9). Strain waves in steel prism were measured at several points with strain gages. Displacement of top of specimen and crack extension were also measured. An example of test data is seen in Fig. 9, in which strain waves measued with the gages of SG2 and SG4, displacement of top of the specimen and the data of crack gages are depicted. From the strain waves measured in steel prism, the wave transmitted to the specimen is obtained by strain wave analysis, and is also shown in the figure. It is known that the crack extend rapidly to the whole section of the specimen within only 150μs (micro second) and the displacement of top of the specimen is quite slight (under 0.4mm) within this period.

From the max. strain of strain wave of 912μ (Fig. 9), the max. applied load to the specimen is estimated at 2070kgf, which is exceedingly less than that in static test (Fig. 8). Besides, the speed of crack extension in this case is very high and reachs about 760m/s in average. Thus shear crack extension is utterly different in impact test from that in static test and Poto. 1 (b), taken with scanning microscope, also shows different feature from Phot. 1 (a). It is considered that these change of crack extension is one of rate effects on concrete.

On the basis of the results of these experiments, it is kown that the countermeasure for brittle fracture, caused in reinforced concrete structures during severe earthquakes, is to limit the relative velocity of displacement in each story and the seeds of crack extension in concrete. It is also important to note that the extension of cracks in concrete can not be restrained by ordinary use of reinforcements.

CONCLUSIONS

1. Brittle fractures, caused in reinforced concrete structures during severe earthquakes, are made by the rate effects on crack extension in concrete.
2. In Mode I (tension crack) tests of concrete, crack extended with exceedingly high speed of extension, nearly 1000m/s, in high rate loading test.
3. In static test of Mode II (shear crack), crack extension was restrained with a large quantity of resisting energy, however, crack extension in impact test was absolutely different and nearly the same speed as in Mode I test was measured.
4. In dynamic design of reinforced concrete structures, the relative velocity of displacement in each story and the seeds of crack extension should be strictly limited.

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