Research paper

Dynamic fracture experiments of mortar using a high-speed loading apparatus driven by explosives

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Received : November 24, 2011 Accepted : March 29, 2012

Abstract

The dynamic fracture experiments of rock-like materials were carried out by using a high-speed loading apparatus driven by the electric detonator. The mortar specimens were loaded in splitting tension and/or bending. The dynamic fracture processes of the materials under high-speed loading were observed by the high-speed video camera system. The dynamic load was measured with a quartz type load cell. In the splitting tension experiment, cracks were firstly initiated near the center of the cross section of the specimen and the cracks propagated to the loading points. It is considered that the crack behavior is affected by the existence of compressive zones near the loading points. The crack behaviors agree with the results of the numerical simulation using the dynamic fracture process analysis code. The tensile strength of mortar under high-speed loading was as much as 100%~140% greater than the static strength. In the bending experiments, three point bend specimens were used. The bending strength of mortar under high-speed loading was also as much as 120~180% greater than the static bending strength.

Keywords : dynamic testing, fracture behavior, loading rate effects

1. Introduction

Most rock-like materials, such as mortar, concrete, are sensitive to the loading rate. Although the materials are generally acknowledged to have a higher dynamic strength than the static strength, for example, the dynamic tensile behavior of concrete has long been considered to be of minor importance to a failure analysis. This is due to the fact that concrete is a structural material most suitable to withstand compressive stresses rather than tensile stresses. However, it became clear that the tensile properties play a dominant role in the failure of concrete structures. Standard static test methods for the tensile behavior, i.e., the splitting tension test and the bending test, are available to determine the static strength, But, dynamic load tests are much more complicated than the static tests and there is a lack of data in tension at higher rates of loading[1),2)].

The higher loading rates can be achieved by using explosives. High-explosives are capable of providing high-energy density at moderate cost and have been utilized. For example, one gram of PETN (pentaerythritol-tetranitrate) at the density, 1.67 g/cm^3 contains approximately 6.1 kJ of energy[3)]. Strong shock loading can be easily achieved by using an electric detonator.

Therefore, the electric detonator is useful as an energy source for the fracture experiment under high-speed loading.

This paper describes the dynamic fracture experiments and the results for the rock-like material, mortar, using a high-speed loading apparatus driven by the electric detonator. The mortar specimens were loaded in splitting tension and/or bending. The apparatus consists mainly of a charge chamber attached to steel frames, a loading piston and a load cell[4), 5)]. The dynamic fracture process of the specimen under high-speed loading was observed by the high-speed video camera system and the dynamic load history was measured by a quartz type load cell. The dynamic fracture characteristics of mortar in tension and/or bending are discussed.

2. Experimental methods

The dynamic fracture experiments of mortar were carried out using the high speed loading apparatus driven by the electric detonator. The loading apparatus is shown in Figure 1[4)]. This figure shows the experimental setup in the splitting tension experiment. The apparatus consists of a charge chamber attached to steel frames, a loading piston and a load cell. The charge chamber was filled with water and the loading piston was driven by underwater explosion of an explosive charge, the electric detonator, in the chamber. The specimen was loaded in splitting tension and/or bending. The dynamic load was measured with a load cell. Figure 2 shows the experimental setup in the bending test. The three-point bent specimen was used.

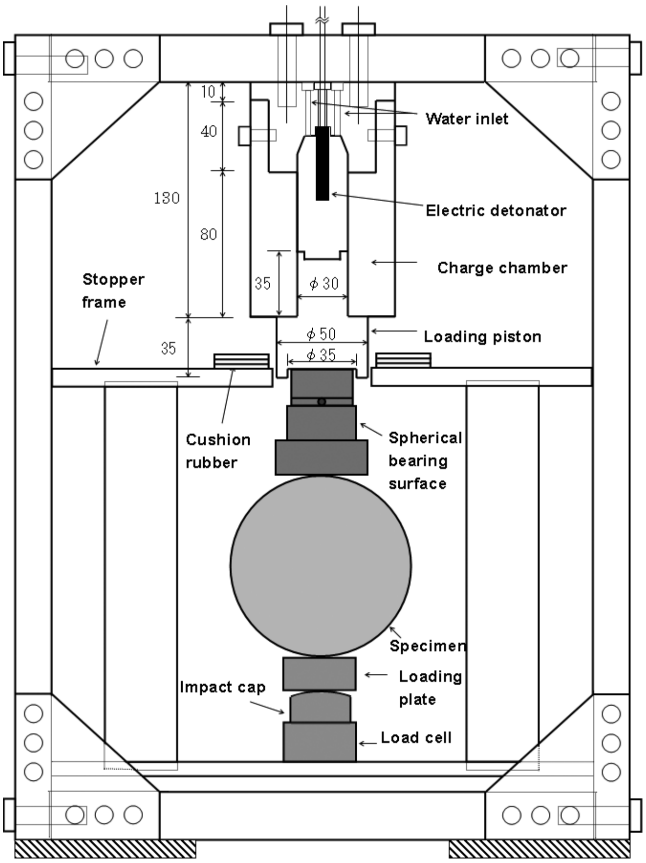


Figure 1 High-speed loading apparatus driven by an electric detonator.

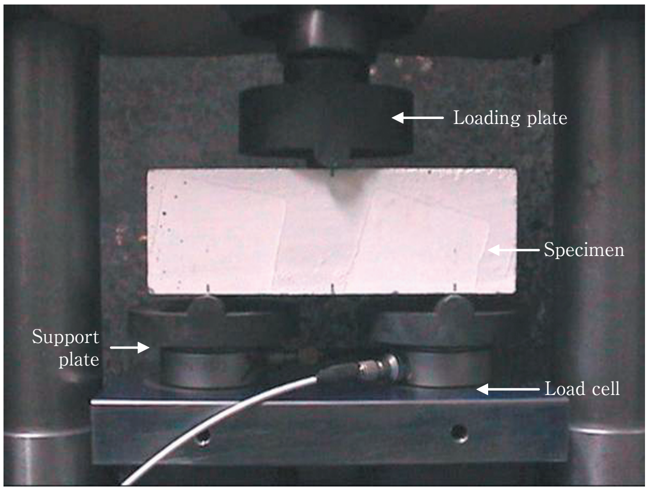
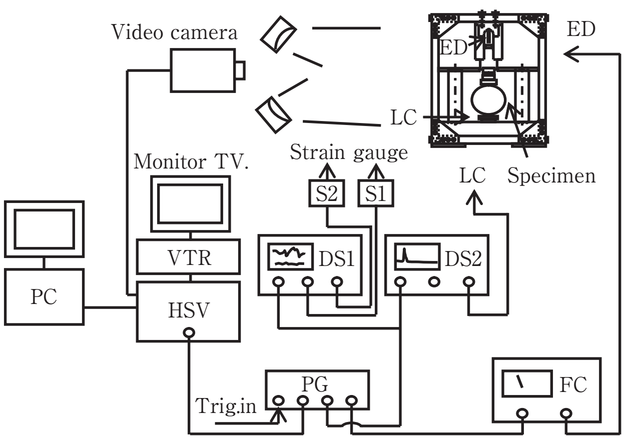


Figure 2 Experimental set up of the apparatus in bending.

The dynamic load was measured by the two load cells attached to each support plate.

The circular disc specimens of 100 mm in diameter and 30 mm in thickness were used in the splitting tension experiment. The specimen was made with the water-cement ratio (W/C), 65% and the static tensile strength was 2.80 MPa at the time that the specimens were tested. In the bending experiment, the specimens with W/C=45% were a rectangular bar with the cross section, 40x40 mm and 120 mm in length and the static bending strength was 8.68 MPa. These values of the static strength are mean values for each experiment using three specimens.

Figure 3 shows the schematic diagram for measurements in the high-speed loading experiments. The dynamic fracture process of the specimen was observed by means of the video camera system of the digital storage type. Framing rates of the video camera can be varied from 30 to 40,500 frames per second. The system is capable of recording 49,152 frames of dynamic events. The high-speed video camera was used in a reflection mode



DS : Digital storage oscilloscope
ED : Electric detonator
FC : Firing circuit
HSV : High speed video system
LC : Load cell
PG : Pulse generator
PC : Personal computer
S : Dynamic strain amplifier
VTR : Video tape recorder

Figure 3 Schematic diagram for measurements in the high-speed loading experiments.

387

with two metal haloid lights. The specimens used in tensile experiments were prepared with white Portland cement and the surfaces of the specimen used in bending experiments were painted white to make the cracks in mortar more clearly visible. The load cell is capable of the maximum load capacity, 133.4 kN and the ringing frequency is 30 kHz. In these experiments, the pulse generator and the firing circuit were used to synchronize the video camera system with initiation of the electric detonator.

3. Results and discussion

3.1 Explosion phenomena of the electric detonator in water

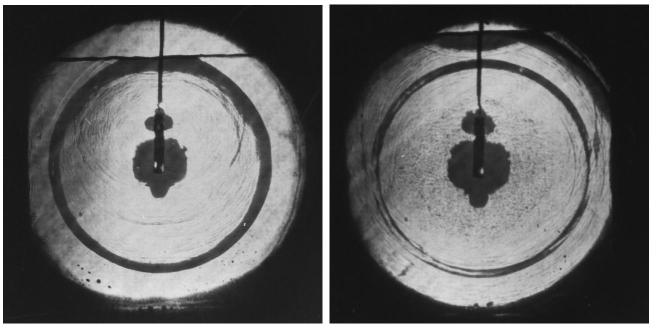
An understanding of explosion process in water of the electric detonator is necessary for the development of the dynamic experimental method. Figure 4 shows shadowgraphs of underwater explosion of the electric detonator[5].

Each photograph is of a different experiment and the time is after initiation of the electric detonator. One can see the dynamic behaviors of shock waves and explosion gases in water. It is interesting to note that the explosion gases from the fuse head were separated from the explosion gas of the main charge. It is also seen that the secondary shock wave was generated in water. The explosion process of the electric detonator in water is related to the loading piston motion of the apparatus.

3.2 Splitting-tension experiments

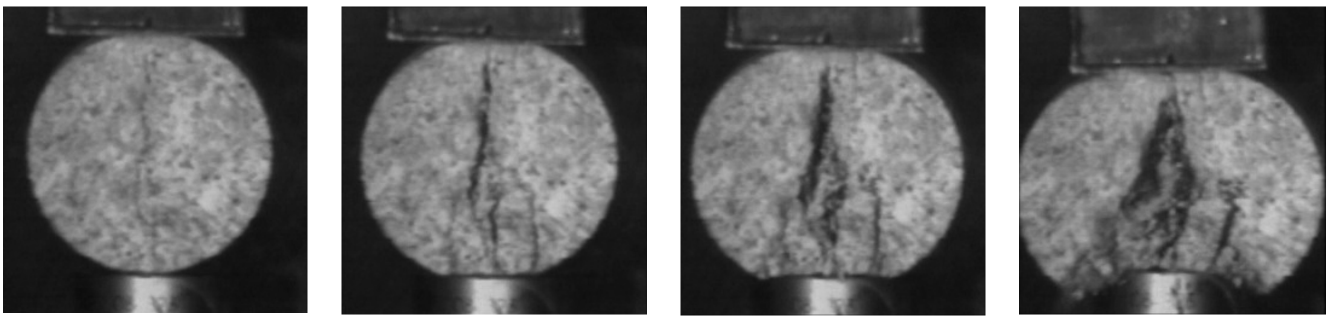
Five experiments were performed under the same condition and the reproducibility of the dynamic fracture process under high-speed loading was examined. Figure 5 shows the dynamic fracture behavior of the specimen under the splitting tensile loading recorded by the high-speed video camera. These video images were taken at the rate of 13,500 frames per second (f/s). The time interval is 74.0 μs for the rate of 13,500 f/s. The frame number is indicated in each photograph of Figure 5. Frame No.1 means the first frame, after the electronic pulse initiating the firing circuit of the electric detonator operated the trigger circuit of the high-speed video camera system. However, it does not mean the first frame after the explosion because of the time delay in initiating the main charge of the electric detonator. In the splitting tension experiment, cracks were firstly initiated near the center of the cross section of the specimen and the cracks propagated to the loading points. It is valuable to examine the effects of aggregates on crack path. Figure 6 shows the dynamic fracture behaviors of the concrete specimen under splitting tension loading[4]. It can be seen from these images that the initial cracks were formed along mortar-aggregate interfaces and the cracks propagated through the aggregates near the loading points. It is considered that the crack behavior is affected by the existence of compressive zones near the loading points.

The dynamic fracture process of mortar in splitting tension experiment was numerically simulated by S.H.Cho using the dynamic fracture process analysis (DFPA) code[6]. The code employs the microscopic strength in homogeneity and the fracture process zone model. The upper of a circular disc was loaded by applying displacement time history. Figure 7 shows numerical results of the mortar specimen in splitting tension. Upper figures show results representing compressive failures and crack propagation. Here, red color indicates the compressive failure zone and the black line indicates tensile crack. The compressive failure was initiated around the upper boundary at 65 μs and lower boundary at 85 μs. The compressive failure areas connected to the cracks after 120 μs. Lower figures indicate the maximum principal stress distribution and crack propagation corresponding to the upper figures. Red portion indicates the tensile stress. Compressive stresses were generated around the upper and lower ends of the model while tensile stresses appeared along the load axis. It is expected that the specimen should experience the peak stress or failure stress between 90 μs and 120 μs. The crack



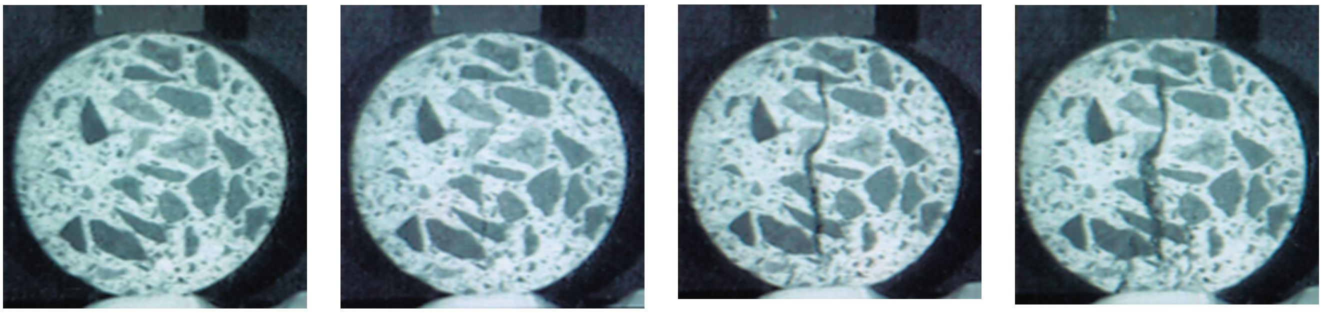
37.5μs 55.7μs

Figure 4 Shadowgraphs of underwater explosion of the electric detonator.



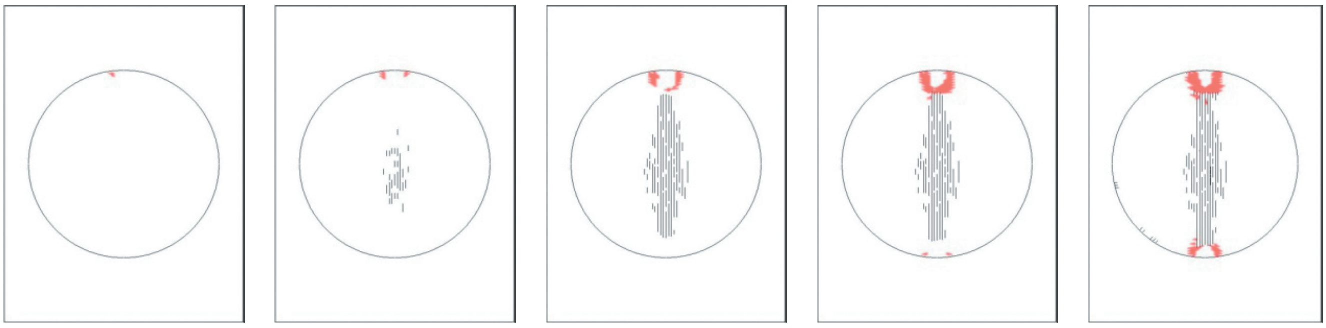
Frame No.8 Frame No.12 Frame No.17 Frame No.28

Figure 5 Video images showing the dynamic fracture process in splitting tension of the mortar specimen (framing rates ; 13,500 f/s).



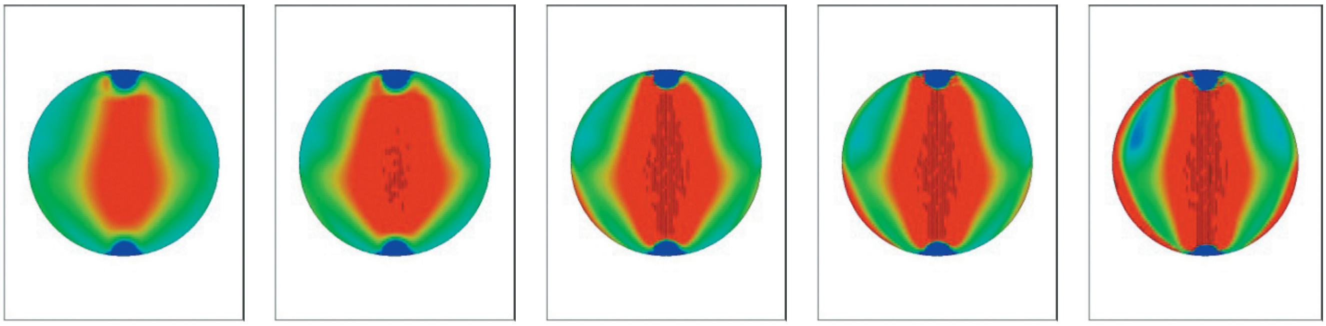
Frame No.8 Frame No.10 Frame No.15 Frame No.20

Figure 6 Video images showing the dynamic fracture process in splitting tension of the concrete specimen (framing rates ; 13,500 f/s).



55µs 65µs 80µs 85µs 115µs

(a) Compressive failures initiated near the loading points and crack propagation



55µs 65µs 80µs 85µs 115µs

(b) Maximum principal stress distributions and crack propagation.
Red color region ; tensile stress, blue color region ; compressive stress.

Figure 7 Numerical results showing the dynamic fracture process of the mortar specimen in splitting tension using DFPA code[6].

behaviors in numerical results agree with the experimental results.

Figure 8 shows the dynamic load history of the mortar specimen subjected to high-speed loading. The time variation of the tensile load was found to be reproducible. In the present experiments, the tensile strength of mortar under high-speed loading with the loading rates 130~170 N/µs was as much as 100~140% greater than the static strength. It was demonstrated that the dynamic tensile strength of mortar increase with increasing loading rate.

3.3 Bending experiments

The five dynamic experiments of the mortar specimens in bending were performed to examine reproducibility of the fracture processes. Figure 9 shows the video images of the fracture process of the mortar specimen.

These video images were taken at 13,500 f/s, the time interval 74 µs. The crack propagated from the middle

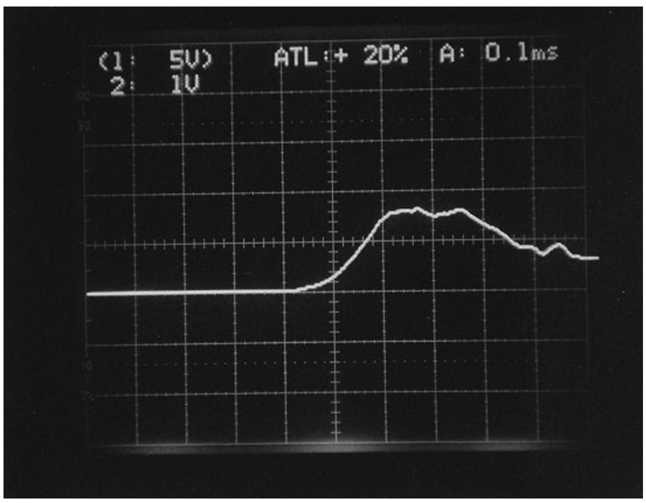


Figure 8 Dynamic load history of the mortar specimen in splitting tension measured by the load cell. Sensitivity ; 17.5 kN/div., time scale ; 100 µs/div.

point of the lower specimen surface to the upper surface and the specimen was divided similar to the fracture behavior in static bending. Afterwards, two cracks are produced in the specimen divided by the first crack. It was appeared from the additional experiments that these cracks were initiated by collision of the edges of the loading plate with the specimen and the cracks propagated from the upper surfaces of the specimen to the lower surface, as shown in Figure 10.

Figure 11 shows the dynamic load history of the load cell attached to the support plate. The time variations of two dynamic loads were nearly identical. The bending strength of mortar under high-speed loading with the loading rates 90~130 N/μs was also as much as 120~180 % greater than the static strength.

4. Conclusions

Dynamic fracture experiments of the mortar specimens in splitting tension and/or bending were performed. The following results were obtained.

(1) The high-speed loading apparatus driven by underwater explosion of the electric detonator is a feasible mean to study the dynamic characteristics of rock-like materials.

(2) High-speed video images were useful in understanding crack behaviors under high-speed loading. In splitting tension, cracks were firstly initiated near the center of the cross section of the specimen and the cracks propagated to the loading points. The crack behavior agrees with numerical results calculated by using dynamic fracture process analysis code.

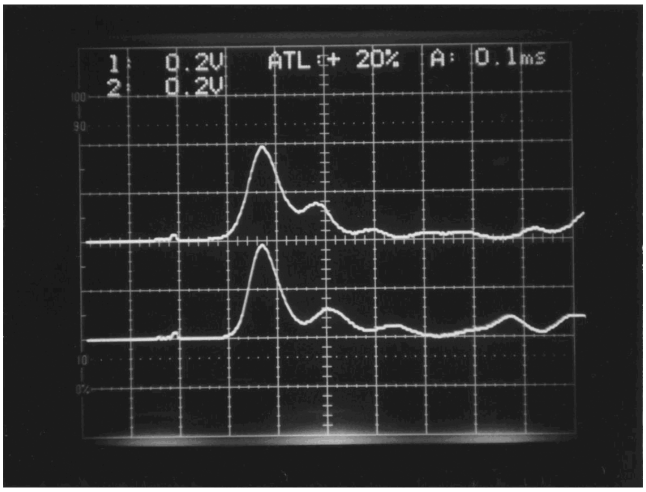


Figure 11 Dynamic load history of the mortar specimen in bending measured by the load cell. Sensitivity; 3.5 kN/div., time scale; 100μs/div.

(3) The results measured by the load cell show that the material strength depends on the loading rate. The tensile

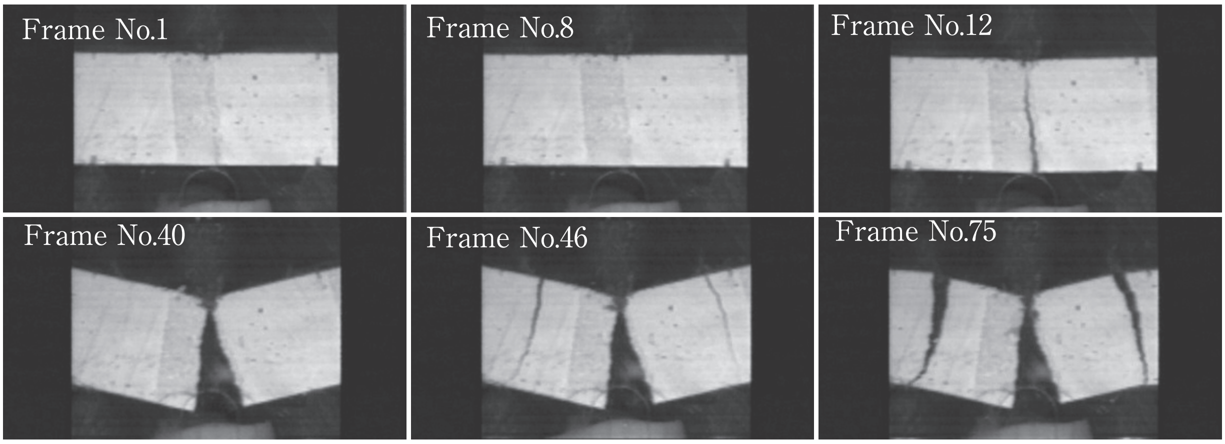


Figure 9 Video images showing the dynamic fracture process in bending of the mortar specimen (framing rates; 13,500 f/s).

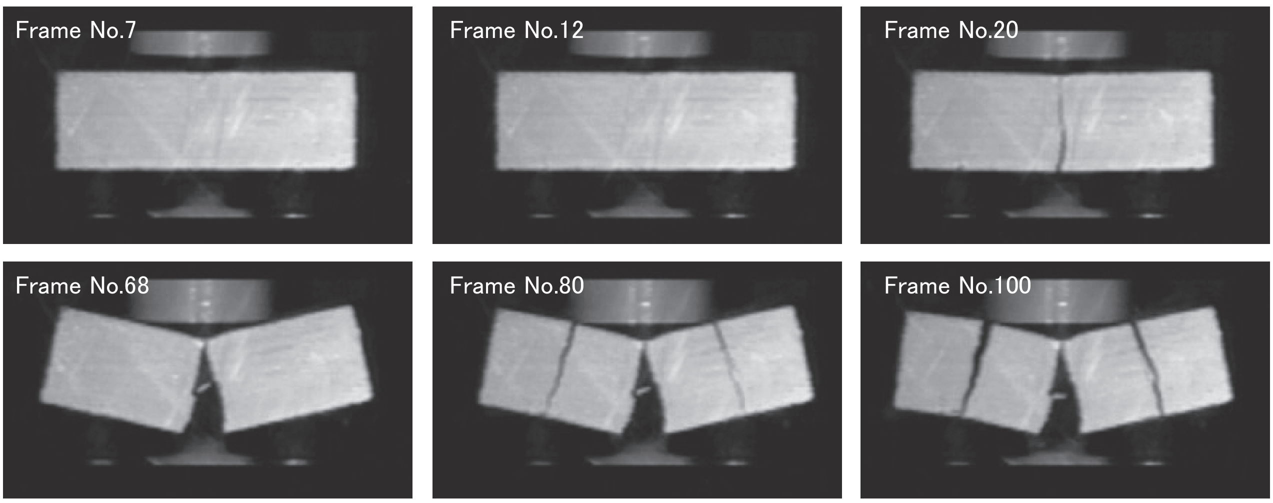


Figure 10 Video images showing the crack behaviors generated by collision of the loading plate with the upper surface of the specimen (framing rates; 27,000 f/s).

strength of mortar under high-speed loading with the loading rates, 130~170 N/μs was as much as 100~140% greater than the static strength. The bending strength of mortar under high-speed loading with the loading rates, 90 ~130 N/μs was also as much as 120~180% greater than the static strength. It was demonstrated that the dynamic strength of mortar in splitting and/or bending increase under higher loading rates.

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