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# Influence of initial static stress on the dynamic properties of concrete

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**Abstract**

Concrete structures prior to being subjected to dynamic loadings such as earthquake have already withstood initial stress. So the study of strain-rate sensitivity of concrete should be closely related to the initial loading history that concrete experiences. Yet majority of available documents concerning the dynamic properties of concrete do not take the initial static loading history into consideration. In this study, experiments were carried out to investigate the effect of initial static stress on the dynamic strength and deformation characteristics of concrete. A prescribed load was initially applied on the specimen at a very low strain-rate and then a dynamic load was applied at a high strain-rate up to failure of the specimen. The relationship between dynamic strength factor and the initial stress is obtained. The comparison between the results by the proposed formula and those by experiments in this study indicates a good agreement. The stress–deformation curves obtained in the tests show that the initial static loading history plays an important role in the total deformation behavior of concrete. An explanation to the physical mechanisms of high strain-rate strength enhancement with different initial static stress was proposed.


*Keywords:* Concrete; Strain-rate; Initial static stress; Strength; Deformation; Failure behavior

## 1. Introduction

Dynamic loading on concrete structures arising from natural hazards such as tornadoes, earthquakes and ocean waves is of great practical concern in civil engineering. Under such dynamic conditions, the strain-rate dependence of the material response causes material behavior to be significantly different from what is observed under quasi-static conditions. Hence a thorough knowledge of material behavior and its constitutive relationships is required to cover a wide range of strain rates, in order to properly design a structure for all types of loading likely to be encountered during the design life span. A considerable amount of research work has been conducted since Abrams [1] observed the rate sensitivity of concrete when he carried out compressive tests in 1917. Bischoff and Perry [2] provide a comprehensive review of compressive behavior of concrete at high strain rates, while Malvar and Ross [3] summarize the dynamic tests of concrete in tension. Gran et al. [4] experimented on high strength concrete specimens using a split Hopkinson Pressure bar (SHPB) at static and high strain rates. However the majority of available work concerning the dynamic properties of concrete does not take initial static loading history into consideration. Virtually, all concrete structures have already withstood static stress prior to being subjected to dynamic loading such as in earthquake. It is necessary to find out whether and how the initial static stress influences the rate-dependent behavior of concrete under dynamic loading. Currently only a limited number of documents are found on this topic. Kaplan [5] experimentally investigated the effect of initial static load on the dynamic compressive strength of concrete; probably he is the first one who studies the effect of initial static load on the loading rate sensitivity of concrete. Ma et al. [6] studied the effect of initial static load through numerical methods. Lin et al. [7] studied

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the influence of initial static load on the dynamic tensile properties of concrete and concluded that initial static loading intensity plays an important role in the enhancement of concrete strength; a higher initial static loading intensity leads to a lower strength enhancement. Zheng et al. [8] studied the influence of initial static stress on the rate-dependent effect of concrete strength based on a single dimension of freedom mathematical model. The dynamic strength of concrete at initial static loading is calculated assuming a single crack model with considering of free water viscosity. Eibl and Schmidt-Hurtienne [9] confirm the influence of loading history on the dynamic strength of concrete and propose a strain-history-dependent constitutive model which takes the full loading history into consideration. To account for the strain-rate effect of concrete under dynamic loading, different assumptions have been proposed. Rossi and Toutlemonde conclude that at strain rates smaller than $1\ s^{-1}$, the main physical mechanism is a viscous mechanism that may be regarded as similar to Stefan effect; while at strain rates higher than or equal to approximately $10\ s^{-1}$, the forces of inertia become preponderant [10]. While Sercombe et al. [11] emphases the viscous effect in dynamic behavior of concrete. Harsh et al. [12] and Yan and Lin [13] investigated the dynamic fracture behavior of concrete in compression and tension respectively. Hence, more work is required before general conclusions can be drawn about the effect of initial static stress on the characteristics of concrete under dynamic loading. To better understand the mechanical behavior of the material, more studies must be conducted corresponding to the range of strain rates and loading paths encountered in the applications of interest.

## 2. Description of the experiment

### 2.1. Specimen

Limited by the capacity of the testing system to carry out dynamic experiments in triaxial stress states in the current research program, the concrete used in the experimental study was designed to have a characteristic compressive strength of 17.0 MPa; the corresponding content proportion of water:cement:sand:gravel was 0.69:1.00:2.63:3.95 by weight. The materials used were Portland cement of type 42.5R, general river sand, crushed gravel (the maximum grain size was 10 mm), and tap water. Concrete mixture was injected in $100\text{-mm}^3$ cubes steel molds that had been precisely machined, then compacted by a vibrating table. Having been demolded the following day, specimens were immersed in a water tank for another 2 days, cured in a fogroom for 28 days, and then air-dried in the laboratory. The relative moisture content of concrete samples was 6.3%.

Dynamic experiments were carried out at the age of more than 600 days after casting. No one group was observed with its one datum exceeding the average of the group by 15% measured during curing. This could ensure the reliability of the test results. It was assumed that the concrete specimens were isotropic before or in the testing.

### 2.2. Testing device

Compressive tests were carried out on a servo-hydraulic testing machine designed and manufactured at Dalian University of Technology, China. The configuration of the testing machine in this investigation is shown in Fig. 1. Load was applied on the specimen through platens; spherical seats existed between the pressure lever and the platen so as to keep the load exerted exactly in the axial direction. Behind one pressure lever, an oil cylinder was installed that could generate load. A load transducer was installed on the other direction to measure the load variation during testing. The nominal capacity of the system was 2000 kN in compression. During the tests, the relative displacement of the cubic specimen in loading direction was measured with linear variable differential transformers (LVDT). Measured signals were transmitted to the data acquisition and processing system of the computer through a specially allocated amplifier. The frequency of data acquisition was as high as $5 \times 10^5$ Hz. The whole process of the stress–strain curve including the descending part was recorded automatically.

### 2.3. Treatment of specimens and test procedure

Prior to the test, the rough surfaces of specimen were polished; sundries on the surface were scrubbed out; and each loading surface was covered with three layers of plastic sheet with MoS2 grease to reduce the surface friction to a minimum. Then, the specimen was placed on experimental apparatus and aligned. The directional loading platens were moved one by one, close but untouched. In order to reduce the initial disturbance of resistance caused by the rough surfaces of specimen, an initial pressure was applied to a certain value (1 MPa in this study) under the control of computer program; then the LVDTs were aligned. The initial voltage of the load amplifier was adjusted, the initial values were collected and the computer acquisition system was set to zero. After this preparation, load was applied until failure of the specimen. Loading patterns are illustrated in Fig. 2. The loading procedure was implemented

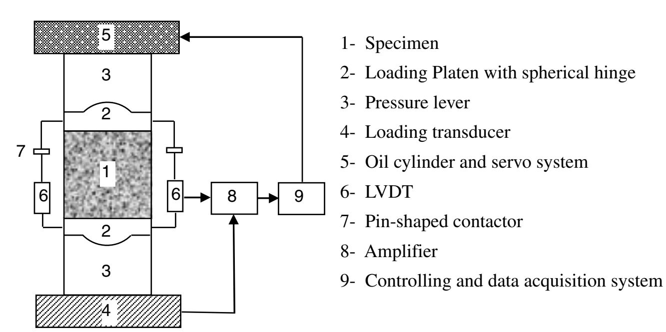



Fig. 1. Schematic diagram of the test setup.

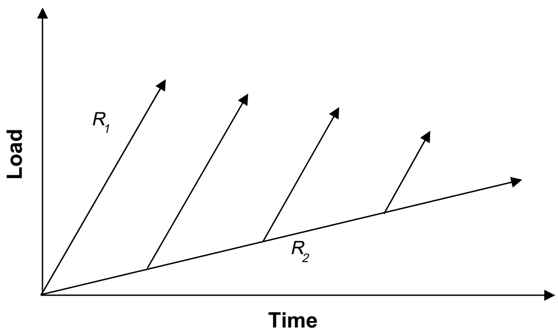


Fig. 2. Loading pattern with different initial static stress.

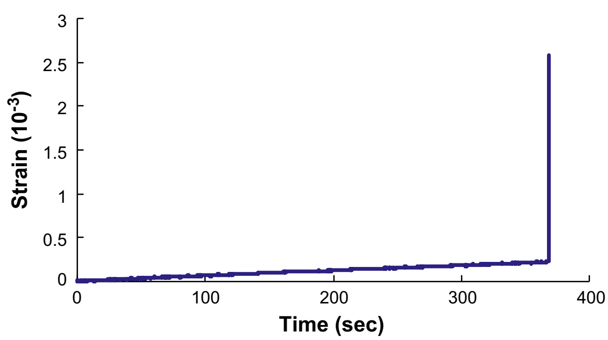


Fig. 3. Measured strain-history.

Table 1
Test results under monotonic-loading (unit: MPa)

| No. | Strain-rate ($s^{-1}$) | | | |
|---|---|---|---|---|
| | $10^{-5}$ | $10^{-4}$ | $10^{-3}$ | $10^{-2}$ |
| 1 | 16.3 | 17.9 | 19.7 | 20.9 |
| 2 | 16.9 | 16.9 | 18.6 | 20.6 |
| 3 | 17.4 | 17.2 | 19.0 | 19.6 |
| 4 | 17.5 | 18.2 | 20.0 | 21.6 |
| Average | 17.0 | 17.5 | 19.3 | 20.7 |

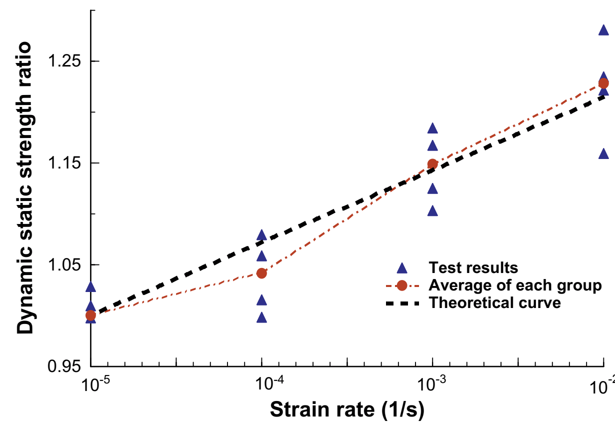


Fig. 4. Strength of concrete under monotonic dynamic loadings.

automatically under the control of the computer program. Typical strain-history measured during a test is depicted in Fig. 3. It can be seen from the figure that a roughly constant strain-rate was obtained in the test, no matter at high strain-rate or low strain-rate. At least four specimens were tested for each loading history case to ensure the repeatability of the experimental results.

## 3. Test results and discussion

To take into consideration more stress states encountered in practice, the stresses of 0, 4.72 MPa, 9.44 MPa and 13.66 MPa, which account for 0, 28%, 56% and 80% of the static compressive strength of concrete, were chosen as initial static stresses. The defined load was initially applied on the specimen at a very low rate, that is, the loading platen moved at a constant speed toward the specimen ($R_2 = 10^{-5}\ s^{-1}$ in this investigation) and then the dynamic load was applied at a higher strain-rate ($R_1 = 10^{-2}\ s^{-1}$ in this investigation) up to failure of the specimen. For comparison, the monotonic-loading tests on specimens at strain rates of $10^{-5}\ s^{-1}$, $10^{-4}\ s^{-1}$, $10^{-3}\ s^{-1}$ and $10^{-2}\ s^{-1}$ were also carried out and the test results are listed in Table 1.

It was observed that the compressive strength increased gradually as strain-rate increased from $10^{-5}\ s^{-1}$ to $10^{-4}\ s^{-1}$, $10^{-3}\ s^{-1}$ and $10^{-2}\ s^{-1}$. The test results are depicted in Fig. 4. It can be seen from the test results that the strength increases almost linearly with a logarithmic increase in strain-rate. Accordingly, a linear relationship between strength and logarithmic strain-rate is assumed as follows:

$$f/f_s = 1.0 + \gamma \lg(\dot{\varepsilon}/\dot{\varepsilon}_s) \quad (1)$$

where $f$ denotes the strength of concrete and $\dot{\varepsilon}_s$ is a quasi-static strain-rate, $10^{-5}\ s^{-1}$ in this paper; $\dot{\varepsilon}$ is the current strain-rate; $\gamma$ is a material parameter determined by least square fitting to the experimental results. In this study $\gamma$ is obtained as $\gamma = 0.071$ with a coefficient of correlation $R^2 = 0.84$. Table 2 shows the comparison of our results with that recommended by the CEB model code [16]. Comparing Eq. (1) with the values given by CEB model code, it is revealed that in our cases strength enhancement with strain rates is smaller than that given by CEB model code.

Table 3 shows the dynamic strengths of concrete with different initial static stresses in this investigation, wherein $\bar{f}$ denotes the average; $f_0$ denotes the initial static stress; $f_d$ denotes the dynamic strength of concrete loaded monotonically to failure at the strain-rate of $R_1$ (loading case 1) while $f_s$ denotes such strength at the strain-rate $R_2$ (loading case 5).

Table 2
Comparison of different formula on the strength enhancement with increasing strain-rate

| | Strain-rate ($s^{-1}$) | | | |
|---|---|---|---|---|
| | $10^{-5}$ | $10^{-4}$ | $10^{-3}$ | $10^{-2}$ |
| CEB model code | 1.00 | 1.12 | 1.25 | 1.40 |
| Eq. (1) | 1.00 | 1.07 | 1.14 | 1.21 |

Table 3
Test results with different initial static stresses (MPa)

| No. | Loading case | $f_0$ (MPa) | $f$ (MPa) | | | | $\bar{f}$ (MPa) | $\bar{f}/\bar{f}_d$ |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | | |
| 1 | $R_1$ | – | 20.9 | 19.6 | 20.6 | 21.6 | 20.7 | 1.00 |
| 2 | $R_2$–$R_1$ | 4.7 | 20.1 | 20.8 | 20.5 | 19.6 | 20.3 | 0.98 |
| 3 | $R_2$–$R_1$ | 9.4 | 19.9 | 18.9 | 20.6 | 20.2 | 19.9 | 0.96 |
| 4 | $R_2$–$R_1$ | 13.7 | 17.7 | 19.5 | 19.0 | 18.5 | 18.7 | 0.90 |
| 5 | $R_2$ | – | 16.3 | 16.9 | 17.4 | 17.5 | 17.0 | 0.82 |

As can be seen from the table, when the initial static stress increases the dynamic strength tends to decrease. When the initial static stress is low, its effect on the ultimate dynamic strength is slight. But when higher initial static stress is initially applied on the concrete, the effect on dynamic strength is more noticeable. For example, when the initial static stress is 13.7 MPa, the dynamic strength obtained is almost 10% less than that under monotonic dynamic loading. A formulas describing the relationship between initial stress and the ultimate dynamic strength is suggested as follows:

$$\frac{f}{f_d} = \alpha + (1.0 - \alpha)e^{(f_0/f_s)^2} \tag{2}$$

wherein $\alpha$ is a parameter depending on the material and the range of strain rate. By fitting to the test data in this study, $\alpha$ is obtained as 1.11 and $R^2 = 0.81$. The test data and the curve of Eq. (2) are depicted in Fig. 5. From this phenomenon it can be concluded that the dynamic strength of concrete is not only affected by the strain-rate at the peak stress point on the stress–deformation curve, but also closely related to the loading history it experiences.

The deformation in the loading direction was measured for all the tests using the devices mentioned above. Fig. 6a illustrates typical relative stress–deformation relationships for different strain rates. As can be seen from the figure, with an increasing strain-rate the ultimate strength and tangent modulus both increase gradually whilst the strain at maximum stress, basically, remains constant. These conclusions coincide well with the results obtained by previous investigators (Bischoff and Perry [2]; Malvar and Ross [3]). The typical relative stress–deformation curves of concrete with different initial static stress are depicted in Fig. 6b–d. At the point where the dynamic load begins to be applied, the slope of the stress–deformation curves changes sharply. It can also be seen from the figures that when the initial static stress is low, for example 4.72 MPa, the stress–deformation curve in the range of dynamic loading is close to that under monotonic dynamic loading. But when the initial static stress is high, the stress–deformation curve will be considerably different from what is observed in monotonic dynamic loading. It should be noted that the initial part (around 5% of critical deformation) of the relative stress–deformation curves in Fig. 6 has been processed to remove the initial disturbance.

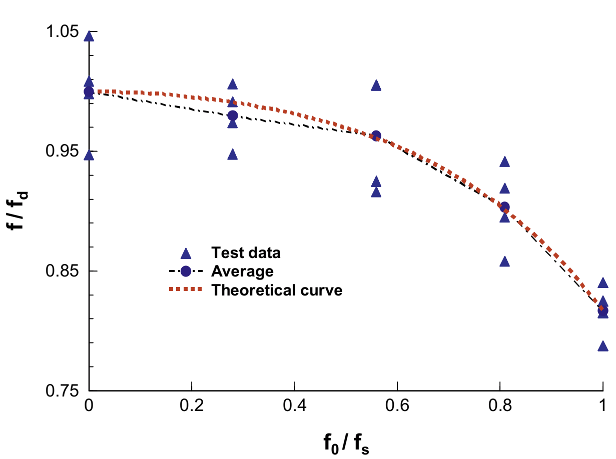
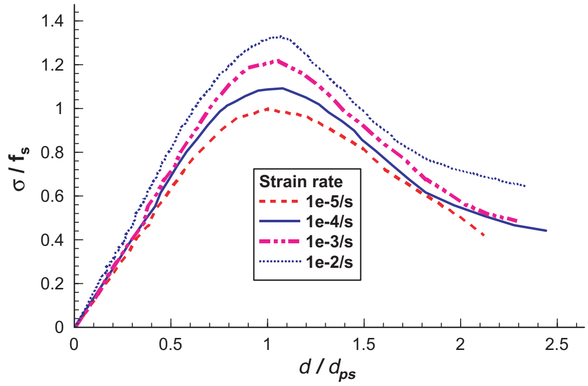
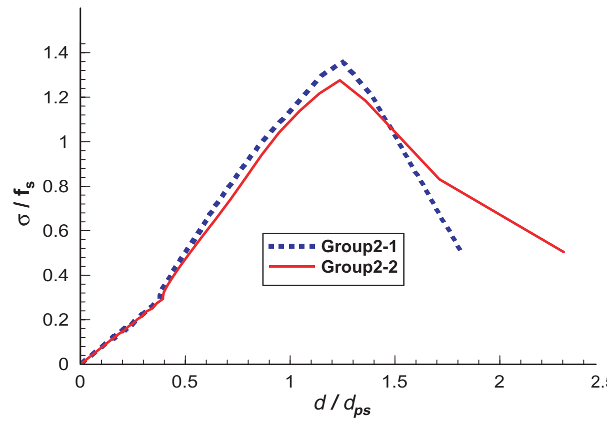



Fig. 5. Initial static stress and dynamic strengths.

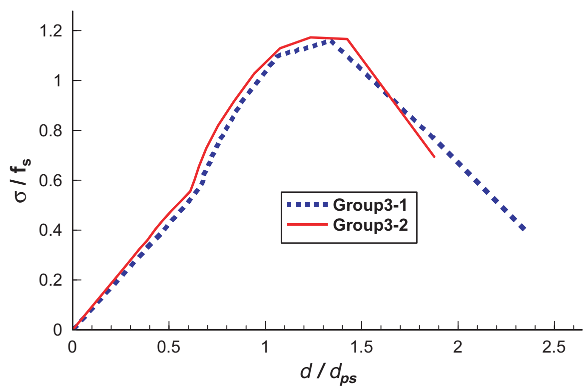
In this study, it was also found that with increasing strain-rate, there were an increasing number of cracks and a louder cracking noise; at the same time, slightly more coarse aggregates were fractured. Since compressive failure is tensile in nature [9], the failure of concrete in compression can be explained by the failure mechanism in tensile tests. Fig. 7 shows typical rupture of specimens at different strain rates in direct tensile experiments (more test details can be seen in Yan and Lin's paper [13]). From Fig. 8 it can be clearly seen that more and more coarse aggregates are fractured with increasing strain-rate. The fracture process of concrete samples in tension is graphically illustrated in Fig. 9. Concrete is a composite material mainly consisting of different sized aggregate particles which are embedded in a cement paste matrix. Many researches have shown that a large number of bond microcracks exist at the interfaces between coarse aggregate and mortar [14]. Under loading action some of the microcracks can be developed due to the difference in stiffness between aggregates and mortar. Thus, the aggregate–mortar interface constitutes the weakest link in the composite system. In case of quasi-static loading, the failure is closely associated with the mechanism of internal progressive microcracking. At first, the bond cracks at the aggregate–mortar interface start to extend owing to stress concentration at crack tips. Then, some cracks at nearby aggregate surfaces start to bridge in the form of mortar cracks, meanwhile, other bond cracks continue to grow slowly. Finally, the microcracks through the mortar coalesce together all the bond cracks and complete disruption occurs. The fracture sur-



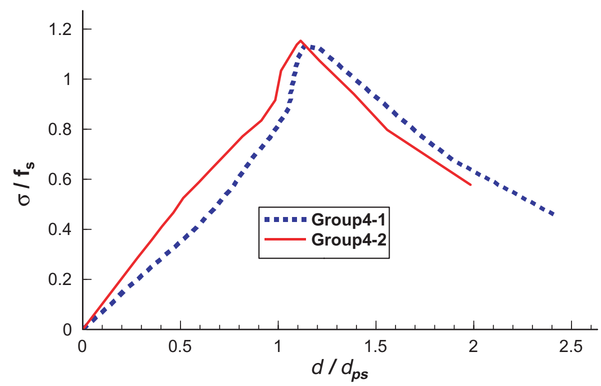

(a). Stress-strain curve at different strain rates




(b). Initial stress is 4.72MPa




(c). Initial stress is 9.44MPa

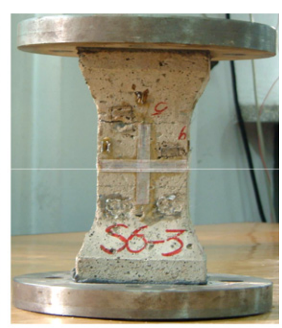



(d). Initial stress is 13.66MPa

Fig. 6. Typical stress–deformation curves.


a. Strain rate: $10^{-5}$ $s^{-1}$


b. Strain rate: $10^{-3}$ $s^{-1}$




c. Strain rate: $10^{-0.3}$ $s^{-1}$

Fig. 7. Typical ruptures of specimen in direct tension.

a. Strain rate: $10^{-5}$ $s^{-1}$

b. Strain rate: $10^{-3}$ $s^{-1}$

c. Strain rate: $10^{-0.3}$ $s^{-1}$

Fig. 8. Typical fracture surfaces of specimen at different strain rates.

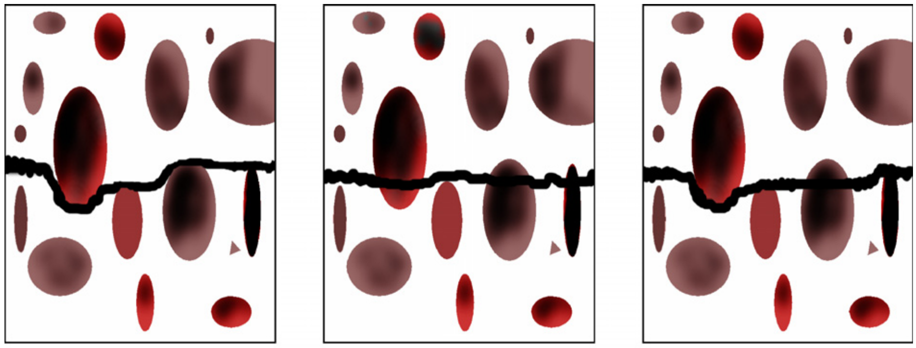



Fig. 9. Illustration of failure mechanism of concrete in tension.

face of the specimen mainly passes through the mortar and the aggregate–mortar interfaces. This leads to a rough surface (see Figs. 7a, 8a and 9a). However, crack velocity in concrete has been shown experimentally to increase with strain-rate [15]. Therefore, at low strain rates crack has time to seek the path of least resistance. However, when subjected to rapid loading, the creation of new cracks is forced to propagate through regions of greater resistance, and a larger number of microcracks may be required before a continuous fracture surface can be formed. Thus, a certain part of coarse aggregates are broken during loading and the fractured surfaces of the specimens become more flattened (see Figs. 7b and c, Figs. 8b and c and also Fig. 9b). The higher the loading rate, the more fractured coarse aggregates. As a consequence, at rapid loading, failure will take place at a higher stress level than that in static loading. It is the higher resistance of concrete material attributed to the strength of coarse aggregates that results in a higher stress level to cause them failure. When initial stress is applied prior to dynamic loading being applied, initial damage accumulates inside concrete. The higher initial stress, the more initial damage accumulation. At the time dynamic load is applied, the fracture of concrete will continue to pass through the rest of the concrete sample following a path that includes more coarse aggregates than in static tests. In this case, the whole path actually, includes less fractured coarse aggregates than in dynamic tests without initial static stress. This is illustrated in Fig. 9c. Thus, the strength will be, to some extent, lower than the dynamic strength without initial static stress.

## 4. Conclusions

The objective of this study is to investigate the effect of initial static stress on the dynamic strength and deformation characteristics of concrete in compression. The conclusions may be summarized as follows:

1. With increasing strain-rate, the ultimate strength of concrete under monotonic-loading tends to increase. The tangent modulus increases with increasing strain-rate while the strain at peak stress does not change much.
2. As the initial static stress increases, the ultimate dynamic strength tends to decrease. The proposed formula of initial static load versus ultimate strength is in a good agreement with the experimental results. At the point where strain-rate varies, the tangent modulus changes accordingly. The change of the modulus becomes more noticeable while the initial static stress increases.
3. Based upon experimental observation an explanation on the physical mechanisms of strain-rate enhancement failure of concrete with initial static stress is proposed. At rapid loading cracks are forced to propagate through regions of greater resistance and thus a higher stress level is needed to lead the specimens to fail. With initial static stress, the failure of concrete will happen in a different way that can induce lower resistance than that without initial static stress.
4. However, further work is also required to deepen our understanding of concrete behaviors, such as the precise description of deformation under dynamic loading, the relevant mechanisms controlling behavior at high strain rates etc; this will allow more accurate constitutive relationships to be established and further implemented into finite-element analysis, which can lead to more confident prediction of the behavior of concrete structures under dynamic loading conditions.

## Acknowledgement

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