Impact of loading rate increase on stress-related properties of concrete

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Abstract. Concrete and reinforced concrete structures of buildings and facilities can be exposed to dynamic loading in which case various kinds of stressed states may occur. To make up the design models of these structures, it is necessary to know the characteristic features of changes in the stress-related properties of concrete, taking account of the joint impact of stressed states and increased loading rates. Several researchers have obtained the data about the impact of the loading rate on the stress-related properties of concrete, mainly for uniaxial compression and under bending [1]-[10], whereas the goal set in this paper is to analyze the loading rate under biaxial compression in which one of the main stresses is generated by static loading and the other by dynamic loading. The study was carried out by experimental research methods. The test results are presented as load-strain charts, plots of changes in strain modules and transverse and dilatational strains. According to the investigation results, the kind of charts is heavily influenced by the kind of stressed state and the loading rate. The analysis of the test data allows making suppositions about the physics of the impact of the loading rate on the peculiar features of concrete strain.

1. Introduction

As a result of an accident or a seismic impact, building structures may be exposed to dynamic loads. The strength and stress-strain properties of materials are included in the structure design model, which is why it is a topical task to carry out basic research in the field of structural material mechanics for the purpose of forming ideas about the aspects of their behavior at dynamic loading as well as about the physical basics of their manifestations.

The material chosen for investigation in this paper is heavy concrete. The data about the impact of the loading rate increase on the properties of concrete has been obtained by several researchers. These studies are mainly concerned with the strength at uniaxial compression. There are relatively few works about evaluating the straining at dynamic action.

The purpose of this paper is to study the joint impact of increased loading rates and the kind of stress state called biaxial compression with different levels of stress σ₂.

It seems that this kind of experimental investigation would allow expanding the notion about the mechanical behavior of concrete at dynamic loading.

2. Methods

The test covered 28 7x7x28 cm sample prisms with internal sensors; final investigation report included the results of testing 25 samples.
Table 1. The distribution of the samples across various loading modes

| Kind of stress state, sidework level | Number of samples of the main size |
|--------------------------------------|-----------------------------------|
|                                      | Statics  | Dynamics |
| Uniaxial compression:                | 3        | 3        |
| Biaxial compression:                 |          |          |
| $\sigma_2 = 0.2R_b$                  | 4        | 4        |
| $\sigma_2 = 0.4R_b$                  | 2        | 3        |
| $\sigma_2 = 0.6R_b$                  | 3        | 3        |
| Total:                               | 12       | 13       |

The dynamic loading was generated at a constant stress increase rate with the average value of $\dot{\sigma} = 470 \text{ MPa/s}$; in that case, the average sample fracture period was 0.08 s. The discreteness of synchronously registering longitudinal and transverse strains as well as axial loading during the dynamic tests was 40 $\mu$s.

The force sensor between the flat jack of the test plant and the sample head was used to register the load.

The strains were measured using internal sensors. These were cylindrical in form and configured as resistance strain gauges covered with an epoxide-sand mix with stress-strain characteristics close to those of concrete. The sensors were fixed in the moulds in three orthogonal directions before the pouring of concrete. The wires pre-soldered to the sensors were led out of the sample.

Other tools used to register the loads and strains were a multichannel electric signal amplifier, an analog-to-digital converter, and specialized software.

Preliminary static stress $\sigma_2$ was generated using membrane units hung onto the respective faces of a concrete sample. In loading phase two, under the influence of stress $\sigma_1$ from zero to destructive values, the specified level of $\sigma_2$ was maintained unchanged.

The experiment allowed attaining longitudinal and transverse strain values bound to the axial load value, which allowed determining the influence of the loading rate on the form of the concrete load-strain chart, strain module, transverse strain factor, ultimate and dilatational strains.

For an example of registering the signal in a dynamic axial compression test see figure 1. The vertical axis indicates the stress registered in MPa and converted to load and strain increments on the basis of a gauging relation.

Figure 1. Sample presentation of signal recording results: 1 is the load, 2 is $\varepsilon_1$, 3 is $\varepsilon_2$, 4 is $\varepsilon_3$
3. Results

The results of testing the concrete are presented in the load-strain charts in figure 2. The load-strain curves superposed in this figure correspond to the different levels of $\sigma_2$ and are derived at both, static and dynamic loading, which allows evaluating most vividly the impact of the stress state and loading rate on the load-strain chart.

![Figure 2. Load-strain curves](image)

3.1. Impact of the kind of stress state on the straining chart

If to consider figure 2 together with figure 3 that shows the change in the differential modules of longitudinal strain from the loading level, it is possible to observe the facts exposed below. The initial module of longitudinal strains is almost independent from the kind of stress state and the level of stress $\sigma_2$. Then, obviously, when the lower microcracking limit is reached, it is seen that the module value is influenced by the variations in $\sigma_2$: the higher is this stress, the lower is the module. At the same time, the module again becomes little sensitive to the value of $\sigma_2$ when coming close to fracture (in the phases of straining from the upper microcracking limit to the limit strength).
In phase two of complex loading by biaxial compression along the effective course of stress $\sigma_2$ and in the free direction the propagation of transverse strains at static and dynamic loading occurs with various transverse strain coefficients ($\nu_{2-1} \neq \nu_{3-1}$). This phenomenon as applied to static biaxial compression tests at complex loading has already been considered in [11, 12] and treated as force anisotropy. A more intensive propagation of transverse strains is observed in the free direction, i.e., $\nu_{3-1} > \nu_{2-1}$. Force anisotropy manifests more intensively with an increase in $\sigma_2$.

### Figure 3. Differential modules of longitudinal strains at static and dynamic loading

The key aspect of the dynamic chart as compared with its static counterpart is an extended length of the initial straight-line section, which shows that concrete has an expanded range of quasi-elastic behavior.

In addition, the general straightening of the dynamic chart is observed: its curvature corresponds to the curvature of the static chart only in the section close to fracture.

This change in the chart appearance indicates that the relation among the components of full strain (elastic, plastic, and pseudo-plastic) changes with an increase in the loading rate. It is clear that not only the so called lag in plastic strain propagation occurs as indicated in a number of works [13, 14] but also the share of plastic strains increases detrimentally to the propagation of plastic strains (considering that the ultimate strain value does not depend on the loading rate).

The comparison of differential modules of longitudinal strains $E_b$ for static and dynamic loading is shown in figure 3. According to the results of this comparison, the initial module of longitudinal strains $E_b$ does not depend on the stress increase rate. Then, after certain stress level $\sigma_1=0.2R_b\div0.5R_b$ is reached, the difference in the values of $E$ begins to grow and the $E_b/E_b$ ratio may reach 1.5 or even higher. It is notable that in the loading phase close to fracture ($\sigma_1 = 0.8R_b$) the dynamic differential strain module tends to come up to its static counterpart.
The indicated dependence of the module on the loading rate and $\sigma_1/R$ is typical for both, uniaxial and biaxial compression.

3.3. Peculiarities of Transverse Strain Propagation at Dynamic Loading

If to compare the static and the dynamic differential coefficients of transverse strain at uniaxial compression that correspond to one and the same value of $\sigma_1$, it is possible to see the trend exposed below. The transverse strain coefficients under static and dynamic action coincide until certain values of $\sigma_1$ (about $0.5R_b$). With the further increase in $\sigma_1$, the transverse strain coefficient at statics increases more significantly than under dynamic action. Thus, $\nu/\nu_d$ is 1.57 at the stresses corresponding to the static strength of concrete.

However, it is worth noting that, if to compare $\nu$ and $\nu_d$ in the loading phases corresponding to the same $\sigma_1/R$ (stress value related to the strength for a given loading rate), it will then appear that they are almost equal. In other words, the transverse/longitudinal strain ratio corresponding to similar straining phases, fracture included, does not depend on the loading rate.

As was noted, force anisotropy generated at biaxial compression in complex loading phase two, shows at both, static and dynamic loading.

However, although the propagation of transverse strains at dynamic loading fundamentally repeats the pattern of straining at static loading, it shows a weaker anisotropy, which is seen from comparing transverse strain coefficients $\nu_{2,1}$ and $\nu_{3,1}$ (figures 4 and 5), load-strain charts, and ultimate transverse strain values.

![Figure 4. Differential coefficients of transverse strain $\nu_{2,1}$ at static and dynamic loading in comparison](image-url)
Figure 5. Differential coefficients of transverse strain $\nu_{31}$ at static and dynamic loading in comparison

3.4. Influence of Loading Rate on Limit Deformability of Concrete and Dilatational Strains

Table 2. Impact of dynamic loading on ultimate strains of concrete at uniaxial and biaxial compression

| Level of $\sigma_2$ | Statics | Dynamics | Compared |
|--------------------|---------|----------|----------|
|                    | $\varepsilon_{1,u}$ | $\varepsilon_{2,u}$ | $\varepsilon_{3,u}$ | $\varepsilon_{1,u,d}$ | $\varepsilon_{2,u,d}$ | $\varepsilon_{3,u,d}$ | $\frac{\varepsilon_{1,u,d}}{\varepsilon_{1,u}}$ | $\frac{\varepsilon_{2,u,d}}{\varepsilon_{2,u}}$ | $\frac{\varepsilon_{3,u,d}}{\varepsilon_{3,u}}$ |
| $\sigma_2=0$       | 186.3   | -83.4    | -83.4    | 168.0   | -84.5    | -84.5    | 0.9      | 1.01    | 1.01         |
| $\sigma_2=0.2R_b$  | 205.9   | -69.5    | -123     | 208.0   | -64.3    | -114.8   | 1.01     | 0.93    | 0.93         |
| $\sigma_2=0.4R_b$  | 234.2   | -45.0    | -154.0   | 247.0   | -60.7    | -129     | 1.05     | 1.34    | 0.83         |
| $\sigma_2=0.6R_b$  | 294.7   | -14.5    | -178.8   | 295.0   | -54.6    | -147.0   | 1.0      | 3.77    | 0.30         |

Our results confirm the data attained by many researchers [13,15]; these data indicate that the ultimate strain at uniaxial loading does not depend on the loading rate.

Another logical trend observed is that the difference in the limit transverse strains (both, $\varepsilon_2$ and $\varepsilon_3$) fixed at static and dynamic loading increases with an increase in $\sigma_2$. This change in the limit transverse strains at biaxial loading is a manifestation of the weakening force anisotropy at dynamic loading, which is considered above.
It is also interesting to analyze the influence of the stress increase rate on the level of dilatational strains (figure 6). The dilatational strains calculated, taking into account the whole load-strain curve and loading phase one, and determined for neighbouring loading phases (at equal $\sigma_1$, related to the strength of concrete for a given kind of stress state, level of $\sigma_2$, and stress rate increase) do not depend on the loading rate increase. At the same time, at equal values of $\sigma_1$ the dilatational strain at dynamical loading is weaker than at static loading.

![Figure 6. Dilatational strains at uniaxial compression and in biaxial compression loading](image)

### 4. Discussion

The load-strain charts derived according to the results of our tests correspond to the current notions about the behaviour of concrete at loading. The charts of both, longitudinal and transverse strains are curvilinear in shape. They have a nearly straight-line initial section, a rising section, and an upper section in which the tangent to the straining curve converges to horizontal.

The analysis of full strains, i.e., considering the strains propagating in loading phase one, matters in terms of explaining the causes of the strengthening effect of $\sigma_2$. It is known that, according to the current notions about the reasons why concrete disintegrates at compression, the disintegration results from the propagation of shearing and tearing strains; moreover, the shearing process is considered definitive. The implementation of the shearing process is evaluated according to the strains propagating along the directions perpendicular to the plane of loads (in our investigations these are strains $\varepsilon_2$ and $\varepsilon_3$ for biaxial compression loading phase two). The material packs along the operative course of stress $\sigma_2$; as a result, the level of $\sigma_1$, at which compression strains $\varepsilon_2$ turn to extension
strains, increases as well. At high levels of $\sigma_2$ this conversion can be impossible altogether, like in our tests at $\sigma_2 = 0.6R_b$. And, although the propagation of transverse strains in the opposite direction does compensate, to a certain degree, the abatement of extension strains in the direction of $\sigma_2$, the tearing cracks are impelled to orientate mainly in one direction, which facilitates the retardation of fracture.

If to analyze the kind of fracture surface, it should be noted that, with an increase in $\sigma_2$, the role of shear obviously grows in importance because the fracture surface is somewhat inclined to the vertical (the propagation of the fracture surface to the sample facets was observed from the side of the planes through which $\sigma_2$ was transferred). The inclination angle increases with an increase in $\sigma_2$ but has never reached $45^\circ$.

The reduction in the difference between $\varepsilon_2$ and $\varepsilon_3$ with a rise in the rate corresponds to the idea that at high rates the redistribution of efforts during loading, thanks to which transverse strains propagate more intensively in the free direction at static loading, is not embodied to the full. At a high rate of force action the taking into account of the existent stress field, which attends the development of straining, is not so full as at static loading, and the equalizing of transverse strain values occurs.

The insensitivity of ultimate strains to the loading rate corresponds to the idea that the ultimate strain is a sort of numerical expression of the amount of microscale fractures that makes concrete lose its strength. It seems fairly justified that the critical volume of microscale fractures must not depend on the way it was generated (nor on the loading rate included).

The results obtained for dilatational strains can also be explained fairly convincingly by the fact that at dynamic loading more stresses are required to form the same amount of microscale fractures than at static loading. At the same time, the amount of these microscale fractures corresponding to the equal phases of straining and fracture does not depend on the loading rate.

5. Conclusions

The stress-strain properties of concrete are influenced by the kind of stress-strain state and the rise in the loading rate.

The concrete strain module significantly increase at the straining between the upper and the lower boundary of microcracking and is almost independent from the loading rate in the initial and final phases.

Force anisotropy weakens with a rise in the loading rate.

The ultimate strains in the direction of stress $\sigma_1$ are little sensitive to the loading rate.

Higher stress values are required to attain equal dilatational strain values at dynamic loading than at static loading. In this case, the dilatational strains corresponding to the equal levels of stresses related to the strength at a given loading rate and stress state take on close values.

The analysis of the aspects of straining at dynamic loading allows making suppositions about the physics of the causes why the loading rate influences the properties of concrete. From this perspective, an important aspect is the change in the correlations among elastic, plastic, and pseudo-plastic strain as parts of full strain in various loading phases. The notion that a certain amount of strains and microscale fractures little dependent on the way they accumulate, the loading rate included, is necessary for switching to various straining phases and for fracture, is proved by the data about dilatational and ultimate strains.

Investigations in a broad range of rates will allow deriving analytical relations for describing straining chart, taking into account the kind of stress state and the loading rate. In addition, these investigations will matter to analyzing the physics of the dynamic strength of concrete.

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