UDC 539.4

Experimental Study of Concrete Subjected to Explosive Loading

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УДК 539.4

Экспериментальное исследование бетона при нагружении взрывом

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Выполненные экспериментальные исследования свидетельствуют о влиянии различных скоростей деформирования на прочность конструкционного бетона. Особое внимание уделено скорости деформирования 10^{-2} c^{-1}, для которой проблематично точно определить механические характеристики квазихрупких материалов. Приведена новая конструкция системы измерения, в которой реализуются компьютеризованное получение, обработка и графичекое представление экспериментальных данных.

Ключевые слова: динамические исследования, нагружение взрывом, конструкционный бетон.

Introduction. Intensive development of the theories describing the behavior under dynamic loading conditions of brittle materials (concretes and rocks) requires experimental verification of these theories. Models of these construction materials, especially in the domain of short-term loads, are not comprehensive unless they are experimentally verified. At present, the experimental techniques for testing of brittle materials, based among others, on the Hopkinson bar method, or those with the use of explosive materials [1] have been developed.

Recently an enhanced development of measurement methods enabling the improved precision in the determination of physical values has been observed. Digital systems of large processing capacities and those of analyzing measurement signals became principal measurement systems. This technology, however, requires costly and precise data sources, the so-called “measurement sensors.”

In the domain of fortification structures, concrete-and-steel reinforced concrete objects are in the most cases kept deep under the ground and during their service can be subjected to the pressure wave loads. Concretes used for the construction, besides their static testing, require verification of their strength under pulse loading of parameters approximating the operational ones. Modern measurement converters and loading stands, working in support on loads generated as a result of rapid burning of powders make it possible to answer those requirements, too.

Characteristics of Loads Used in the Dynamic Tests. A pressure wave load of variable increasing time, up to its maximal value and of duration depending on powder grain diameter is obtained while using nitrocellulose powders of various grain gradients for combustion in a generator of a specially designed loading stand, characteristics of which have been presented in [3] (see Fig. 1).

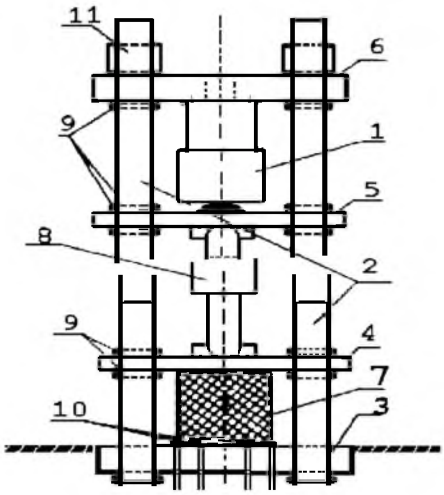

Fig. 1. Scheme of the experimental set-up for dynamic tests of structural materials: *1* – dynamic loading generator, *2* – steel columns, *3* – lower foundation plate, *4* – lower sliding plate, *5* – top sliding plate, *6* – fixed plate, *7* – investigated specimen, *8* – hydraulic servo.

The time of the load increase to its maximal value was 24.6 ms, while the loading duration did not exceed 50 ms. During the experiment, the specimen did not break, but distinct cracks could be seen on its surfaces.

In further fracturing testing aimed at the determination of structural concrete strength in compression, only the rising branch of the pressure wave is used for determination of the value of fracturing force. On the other hand, it is controlled by the amount of powder of the given grain gradient, portioned in to the generator combustion chamber.

Measurement System. Determination of the strength of structural concrete in compression under dynamic loading by pressure wave and the development of the stress-strain relationship diagram were adopted as the main goal of this study. Experiments were conducted on standard cubic specimens ($150 \times 150 \times 150$ mm). Measurement of stresses was carried out directly by recording the liquid pressure variation in the hydraulic operator (measurement in point *1*, Fig. 2). Cubic concrete specimen was placed between the two steel interface liners of hardened surfaces, each being 10 mm thick. Contact surfaces were covered with oil. Such procedure made it possible to partially eliminate the shear stresses occurring at the specimen/plates contact zone. The EA-06-10CBE-120 foil resistance strain gauges of 30 mm measurement base and 120 Ω resistance were glued on the surface of the specimen under study and used for measurement of the concrete strain.

ISSN 0556-171X. Проблемы прочности, 2002, № 3

During the experiment, vertical ε strains (point *4*) and the horizontal ones (point *5*) were measured by connecting the strain gauges to the full bridge system (Fig. 2) with two compensation strain gauges balancing the effect of temperature.

Strain gauges were glued on the opposite walls of the cubic specimen. The recording of global deformation of the tested specimen along with the slide of the upper sliding plate were carried out with a transformer differential displacement sensor by placing it at the point *2*. Taking into account the sensor possible damage, the plate sliding distance was limited to 6 mm. Moreover, the slide velocity of the plate V-point *3* and vibrations in measurement points *6* and *7* were registered. All values were registered by an indirect method as electric potential changes in the function of time, corresponding to the changes in the individual parameters of physical values. In order to determine the static strength, six specimens from each series were subjected to static tests carried out at the standardized velocity of load increase: 0.2–0.3 MPa/s. Static tests were made on a hydraulic press with the ability to generate forces up to 1500 kN.

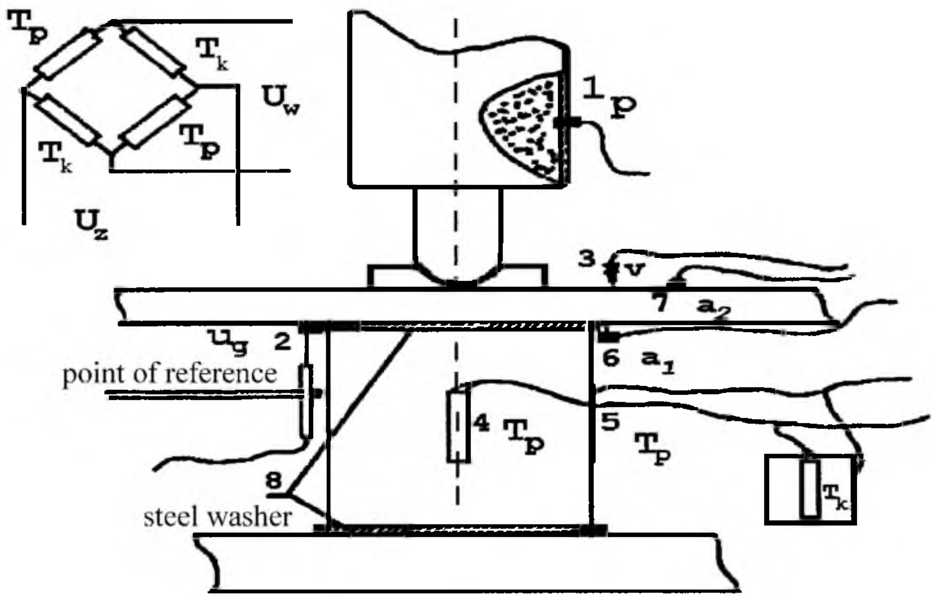

Fig. 2. Distribution of measurement points on the testing stand.

Computerized Measurement System. Each investigated physical value was recorded on separate measurement tracks, realizing the feeding of measurement sensors and processing the input signals from the sensors into the og output signals of 0.5–10 V. All bridges and amplifiers had a transmission band of 0–20 kHz which enabled recording of rapid variability processes. As far as all recorded signals are in the analog form and there is no possibility of clear determination of the time interval starting, from the moment of the feeding source switch-on till the ignition of the powder charge, a measurement tape-recorder has been chosen as a recording tool.

In this case, it is the 8-channel recorder of the Racal company. This recording unit enables a simultaneous recording of runs of eight analog values on a VHS tape of enhanced magnetic properties. The recording is realized in a FM modulation mode in the 0–100 kHz band. At the output, the analog signal of 1 V amplitude is obtained, which is then subjected to sampling and encoding by the DAS-16F analog-to-digital converter. Further analysis in the domain of time and frequency and appropriate processing is conducted with the use of computer systems or special analyzers (e.g., spectral ones) and the ASYST software.

Results. Twenty specimens of structural concrete of the B30 class of component ratio w (water) : c (cement) : k (aggregate) – 1 : 1.12 : 11.76, on the Polish Portland cement basis were prepared for testing.

All-in aggregate of a 0.5–8 mm thickness fraction was used as a concrete aggregate. Static and dynamic strength tests were carried out with the average load velocity of 0.14 MPa/s corresponding to the average deformation rate of 52 μm/s. For the investigated specimen series, the average compression strength of the concrete was $R_c = 30.88$ MPa. The maximal increase of local vertical deformations in the analyzed specimen series was $\varepsilon = 1280$ μm/m. The average time of the load increase up to the fracture was 230 s.

The dynamic testing in the case of the series discussed was conducted only at one velocity of the load increase, equaling on the average to 1505 MPa/s (corresponding to the load generated by burning of the "Buk-type powder" of the combustible layer of thickness $i = 2.2$ mm). Examples of the "stress vs time" and "strain vs time" diagrams are presented in Fig. 3.

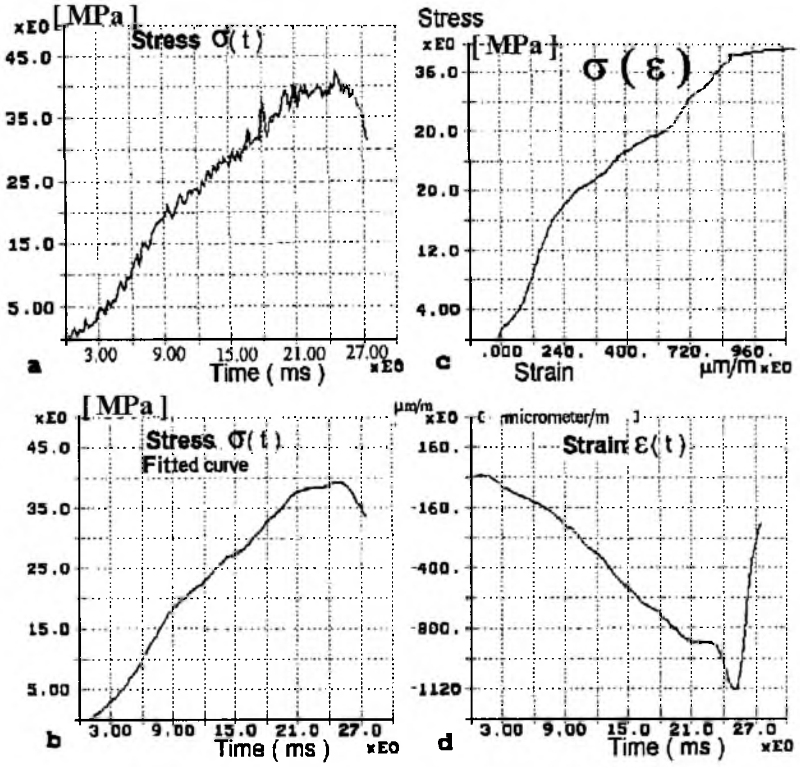

Fig. 3. Typical stress and strain diagrams at the loading rate of 1505 MPa/s.

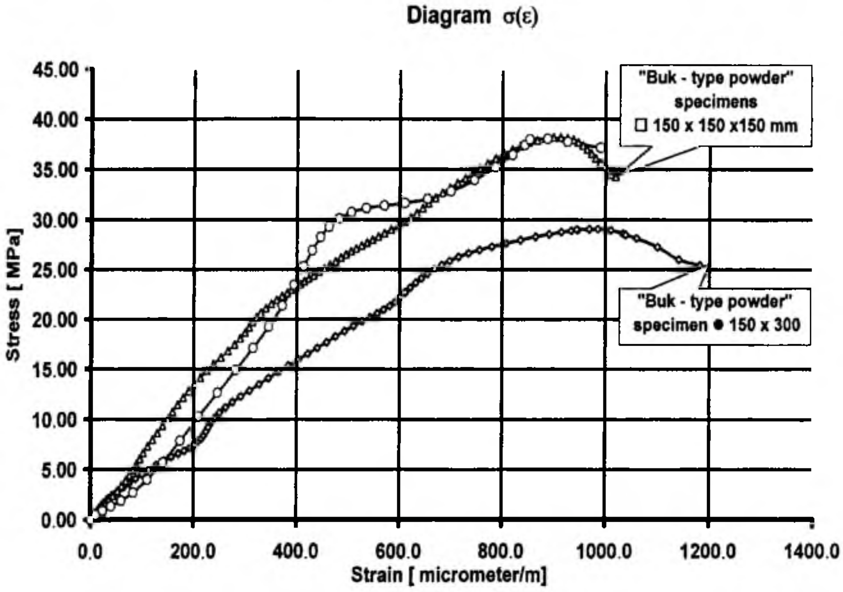

Fig. 4. Typical "stress–strain" diagrams for three different (two cubical and one cylindrical) concrete specimens under the loads generated by burning of the "Buk-type powder."

The average strength of the concrete in compression (as calculated from ten samples), under the dynamic load was $R_c^d = 38.99$ MPa. The average value of maximal vertical deformation was $\varepsilon = 1120$ μm/m.

The average time of the load increase up to the moment of the specimen fracture was 27 ms. Based on the medium values of the delta courses, determined by digital methods with the use of digital filtration and the so-called "smoothing windows," the final plots of the local stress/strain relationships $\sigma(\varepsilon)$ were prepared (see Fig. 4). The elastic modulus of the concrete in compression E_c was determined from the relationship [2, 3]:

$$E_c = \frac{0.4R_c - 0.5}{\varepsilon(0.4R_c) - \varepsilon(0.5)} \quad [\text{GPa}], \tag{1}$$

where $\varepsilon(0.4R_c)$ is the strain corresponding to the stress of $0.4R_c$ [MPa]; $\varepsilon(0.5)$ is the strain corresponding to the stress of 0.5 MPa.

The elasticity modulus of the concrete at the load rate of 0.14 MPa/s was 26.8 GPa, while at the loading rate of 1505 MPa/s this parameter was 45.6 GPa.

Conclusions

1. The tests performed have shown that there exists a possibility of conducting the verification testing of dynamic strength of structural concrete in compression using standardized specimens.

2. With increasing loading rate, the strain level in concrete decreases what can be attributed to the vanishing of elasticity face of the material (brittle fracture occurs).

3. In the tests performed, the increase in the material strength by 1.26 at dynamic loading as compared to the static one, while the corresponding increase in elastic modulus equaled to 1.7.

4. The technique proposed makes it possible to conduct testing of structural concrete under dynamic loading conditions at a predetermined velocity of the load increases increase up to the moment of specimens fracture.

Acknowledgement. This paper was prepared within the framework of the research project No. 0T 00A 017 15 financed by the State Committee for Scientific Research (Poland).

Резюме

Проведені експериментальні дослідження свідчать про вплив різної швидкості деформування на міцність конструкційного бетону. Особлива увага зосереджена на швидкості деформування 10^{-2} c^{-1}, для якої проблематично точно визначити механічні характеристики квазікрихких матеріалів. Наведено нову конструкцію системи вимірювання, в якій реалізуються комп'ютеризоване одержання експериментальних даних, їхня обробка та графічне зображення.

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Received 14. 11. 2001