The degree of survivability of building structures under dynamic loading

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Abstract. The relevance of the work is due to the increasing possibility of impact on the critical building structures of industrial buildings of short-term dynamic loads in abnormal emergencies. These situations lead to significant damage of the constructions of buildings. There is a high possibility of human victims and significant damage of expensive technological equipment when the structures collapse. Therefore, in order to ensure further functioning of the structure, it is necessary to design building structures as well as the object on the whole with the properties of survivability under non-stationary impact. Such properties should be analyzed when constructing scenarios of origination and development of emergency situations as well as analyzing risks. In the course of the research the strain gauge methods were used to measure deflections, accelerations and loads on the samples. The work proposes a method for assessing the degree of survivability of a critical building structure under short-term dynamic loading based on the analysis of the energy parameter. Using the example of a specific test of a bending reinforced concrete element for short-term dynamic load the values of the specified coefficient were obtained.

1. Introductions
At hazardous production projects there is always an increased possibility of emergency occurrence due to which explosions and impacts on building structures of short-term dynamic loads can occur. Such loads are characterized by a sharp rise of front, a short duration of action and a wave character of impact.

During the construction of these facilities the monolithic or prefabricated reinforced concrete is often used for the construction of load-bearing frames of buildings and structures.

The main requirement for load-bearing building structures in the case of emergency impacts is the preservation of the bearing capacity while the deflections and deformations are generally not standardized and in order to save money during designing all the resources of plastic work of the material can be used. In fact, the structure must have the property of survivability when exposed to short-term dynamic loads. The use of the methods of the theory of survivability of technical systems [1-8] and the static and dynamic assessments of functioning of technical objects allows us to determine more accurately the residual life of building structures as well as buildings and structures after the effects of excessive dynamic loads.

The complexity of the processes occurring in reinforced concrete under a short-term dynamic action [9–17], especially in the plastic stage of material operation, makes experimental studies an integral part of the design of such structures.
At the same time, the experimental studies have limitations in terms of availability of the necessary equipment and methods of its use (the possibility of installation and application, avoidance of damage due to high cost, reproducibility of the data obtained, etc.).

Thus, the researchers are faced with the task of creating accessible methods for processing and interpreting information obtained in experimental studies with the possibility of their practical application. Such methods should be reproducible and applicable when testing structures with different dynamic parameters.

The paper proposes a technique for assessing the degree of survivability of critical building structures under shock-wave loading. As an example, the test of a bending reinforced concrete element under the action of a short-term dynamic load is considered.

The aim of the work is to create a practically applicable method for assessing the degree of survivability of a building structure under short-term shock-wave loading based on the analysis of the energy parameter.

2. Methods

Investigations of the work of a bendable reinforced concrete element were carried out on the action of a shock load on the basis of a pile driver. The prototype was a reinforced concrete beam with a length of 2.0 m, a cross-section of 90 * 180 mm reinforced with four longitudinal reinforcement rods with a diameter of 10 mm, class A400. The conditions for fixing the specimen were hinged; the scheme was single-span; the calculated span was 1.8 m. The specimen was deformed by transferring the energy of a load weighing 430 kg falling from a height of 0.5 m. The model and implementation of the stand are shown in figure 1.

To control the load value during the experiment a force-measuring tensoresistive DST4126 type sensor with an allowable force under static action of up to 2000 kN (with a short-term dynamic loading up to 200 kN) was used, the pressure control was carried out by means of dynamometer - 2 pcs. A sensor for measuring the load from the falling weight was installed in the middle of the span of the distribution crosshead. To achieve the required time of action of the load on the sensor a set of rubber gaskets was installed from above.

Accelerometers ARF-10000A and deflection meters WayConRL150-G-SR were installed to record accelerations and deflections at the control points of the experimental sample (five points evenly distributed along the length). To register the readings of all sensors during the experiment the certified measuring systems MIC-300m and MIC-036r were used.

![Figure 1](image-url)  
**Figure 1.** General view of the test bench: a) model; b) implementation; 1 - pile driver; 2 - a load weighing 430 kg; 3 - bomb release; 4 - force measuring device; 5 - distribution traverse; 6 - experimental sample; 7 - support; 8 - power floor; 9 – safety equipment.
3. Results
From various sources [18, 19] it is known that under the short-term dynamic action the strength of reinforced concrete structures is increased relative to the strength under the static loading that is explained by the change in the physical and mechanical characteristics of concrete and reinforcement. Under the short-term dynamic loading there is an uneven development and some delay of deformations in comparison with the results of static tests. In addition, under such influences the forces, torques and bending moments of two planes in various combinations can occur in the load-bearing reinforced concrete elements [20, 21]. The above said with considering the shortness of research significantly complicates the process of registration, processing and analysis of data.

Previously, the authors proposed an approach using the coefficients of the resultant force [22] to assess the performance of a structure under the short-term dynamic impact where only the acting load and support reactions were used.

After the completion of the experiment the received initial signals from all the sensors were converted into xls (Microsoft Excel) format, the calculations and processing of the results were carried out in this program.

The research task was to assess the energy parameter during the movement of the structure in the process of its deformation. Accordingly, it was necessary to determine the work of forces on the given displacements at each moment of time. Thus, it was necessary to have the initial signals of external forces, deflections, and accelerations to find the arising inertial forces. According to the d’Alembert principle the inertial forces must be taken into account to formulate the equations of equilibrium of a structure under dynamic loading.

After receiving and processing the data from acceleration, deflection and force measuring sensors [23], a graph of the forces work at specified displacements was plotted for a time period of 70 ms. In accordance with Cliperon’s theorem, when a group of external forces acts on an engineering structure the work of these forces is equal to half the sum of the products of each force by the value of the corresponding displacement caused by the action of the entire group of forces. The formula for determining the work at each moment of time (1) can be represented as:

\[ A(t) = \left( \frac{F_f(t)}{2} + F_{i1}(t) \right) * f_1(t) + \left( \frac{F_f(t)}{2} + F_{i2}(t) \right) * f_2(t), \]

where \( A(t) \) is the work of forces on the given displacements at each moment of time (J); \( F_f(t)/2 \) - the force recorded by the force meter during the test, divided by 2 to obtain the magnitude of the force at the point of its transfer to the sample through the support of the distribution beam at each moment of time (N); \( F_{i1}(t), F_{i2}(t) \) - conditional forces of inertia reduced to the places of application of forces on the sample at each moment of time (N); \( f_1(t), f_2(t) \) - deflections of the specimen at the point of transfer of external forces to it at each moment of time (m).

The resulting work schedule for 70 ms is shown in figure 2.

![Figure 2](image-url) The graph of work changes over a period of time 70 ms.
4. Discussion

In the presented experimental study the increase in the internal energy of the sample is due to an increase in the potential energy which is associated with the mutual arrangement of the molecules of the body during its bending. If we are dealing with elastic deformation, then after removing the load due to the internal energy the elastic forces bend the sample. It is known that in the course of elastic deformation the temperature of solids does not increase significantly but during plastic deformation the solids can significantly increase their temperature. The increase in temperature and, consequently, in the kinetic energy of molecules reflects an increase in the internal energy of a body during plastic deformation. In this case, the increase in the internal energy also occurs due to the forces that cause deformation.

If we estimate the difference between the energy over the time period characterizing the downward movement of the sample (up to the maximum deflection) and the elastic deformation energy due to which the sample moves upward (the time period from the maximum deflection to the maximum bending), it will be possible on the basis of the law of energy conservation to estimate the total amount of energy spent on destruction (plastic deformation), vibration motion of colliding bodies, the energy converted to heat, etc.

It is technically and mathematically very difficult to take into account and accurately decompose the energy into all the indicated components under the short-term dynamic action. Therefore, within the frame of practical application for assessing the survivability of an experimental sample, the authors proposed a coefficient of the degree of survivability which expresses the ratio of the total transferred energy to the elastic deformation energy of a solid at one full vibration (deflection and bending).

To obtain energy one should find the area under the graph of work depending on time (figure 2) for the required periods of time (inflection and deflection). This can be done graphically or analytically by integration. It is possible to calculate the value of the coefficient of the survivability degree of using the analytical dependence (2) given below:

\[ k_{d.s.} = \frac{\int_{t_p}^{t_v} |A(t)| \, dt}{\int_{0}^{t_p} |A(t)|/dt} \]

where \( k_{d.s.} \) – the coefficient of the degree of survivability of a sample; \( A \) – work of forces on the given displacements at each moment of time (J); \( t_p \) – time of maximum deflection (s); \( t_v \) – time of maximum (stabilized) deflection (s).

In a graphical form the determination of the coefficient of survivability degree for the investigated sample is given in figure 3. Here, for the convenience of displaying information the values of work are converted into relative units by dividing on the maximum value - the maximum value of the work of forces at given displacements for the entire time period of calculations (J). In figure. 3, the area (shaded in red) corresponds to the total relative energy, and the area (shaded in green) corresponds to the relative energy of elastic deformation of the sample. To obtain the absolute values of energies from the graph one should multiply the corresponding areas by the value.

As it is seen in figure 3 for an exemplary test the value of the coefficient of survivability degree of the sample was the following.

The use of this approach makes it possible to obtain a qualitative and quantitative picture of the energy distribution process under a short-term dynamic impact on a bent reinforced concrete specimen and to estimate the degree of survivability of the specimen expressed through the coefficient of degree of survivability.

The developed technique and coefficient of survivability may be useful in design and evaluation of the effectiveness of protective systems on flexible supports and vibration damping systems to cushion the dynamic impact on reinforced concrete structures under seismic, emergency shock or explosive loads [24, 25].
Theoretically, one may calculate the value of the survivability coefficient over the entire time interval of the sample oscillation - until it stops completely. However, the calculations become much more complicated, and the amplitudes of the following oscillations are much less than during the first deflection and bending of the sample due to the damping of oscillations (that is, the calculation error is likely to be not significant). Thus, for the purpose of practical application the survivability coefficient is recommended to be evaluated only for a time interval corresponding to one full period of sample vibration (deflection – bending).

To obtain more complete data on the process of energy distribution that occurs during a short-term dynamic impact on a reinforced concrete sample one should assess the deformations of concrete and reinforcement of the experimental sample and get out through them to the volume of destruction energy (plastic deformation energy). The developed technique can be applied to estimate the degree of survivability of various types of building structures as well as at different time intervals of its action.

5. Conclusions
A method for estimating the degree of survivability of critical building structures under shock-wave loading using the coefficient of survivability degree based on the energy parameter was proposed. On the example of a specific test of a bent reinforced concrete element for a short-term dynamic load the value of survivability degree of survivability obtained was equal to $k_{d,s.} = 0.246$.

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