Assessment of energy efficiency of yielding supports for reinforced concrete beams under dynamic loading

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Abstract. When designing reinforced concrete structures subjected to intense dynamic loading, it is necessary to take into account the simultaneous influence of the thrust reaction, which leads to significant increase in strength and crack resistance, and the influence of yielding supports used to increase the energy intensity of structures. The purpose of this study is to assess feasibility of yielding supports application in thrust structures. The paper presents results of experimental studies of reinforced concrete beams with thrust on yielding supports under short-term dynamic loading. The paper considers the influence of thrust on strength, deformability and crack resistance of reinforced concrete structures under short-term dynamic loading, as well as the joint application of yielding supports and limitation of horizontal displacement of the support contour. The results of the study indicate positive effect of yielding supports application in structures with thrust.

1. Introduction
The factors of emergency impact on building structures can be referred to as: damage and defects in building structures, technical problems with equipment, deviations from design solutions during construction and installation of hazardous industrial facility, high wear of equipment, and insufficient level of new technologies implementation. The occurrence of an emergency is becoming an increasingly urgent problem every day, which leads to significant socio-economic problems: destruction of structure or its part, suspension or complete cessation of all technological processes, injuries and deaths of people providing service for the production process.

When designing buildings and structures, special attention should be paid to enhancement of the methods for calculating and analyzing the stress-strain state of building structures under short-term dynamic emergency loads [1-7].

The paper presents assessment of energy efficiency of yielding supports application [3, 7] in reinforced concrete beams with thrust under intense dynamic loading. As an example, authors provide the analysis of test results of reinforced concrete beam under the action of short-term dynamic loading, as well as reinforced concrete beam with thrust on yielding supports under short-term dynamic loading.

2. Materials and methods
In order to assess energy efficiency of yielding supports and the stress-strain state of reinforced concrete beams with and without thrust under short-term dynamic loading, two design structures were
tested: B – beam without thrust on non-movable supports and BS – beam with thrust on yielding supports.

Reinforcement is performed by spatial framework for both B sample and BS sample. As transverse reinforcement, cold-deformed reinforcement Ø5 mm of Bp500 grade was used, installed with a pitch of 50 mm in the support zone and 130 mm in the middle of the span; and as longitudinal reinforcement – hot-rolled reinforcement Ø 6 mm of A240 grade in the compressed zone and Ø10 mm of A500 grade in the extended zone was used. To strengthen the end sections of the beams, authors used grids with a cell of 50 × 50 mm from cold-deformed reinforcement Ø5 mm of Bp500 grade with 7 grids on each side and angles of 100 × 10 mm were installed.

During the test, a set of measuring instruments was placed on the structures (Figure 1): for determining displacements – Waycon RL150 series inductive displacement sensors (Figure 1, pos. 2); for measuring accelerations – accelerometers (DHE 100023) (Figure 1, pos. 3); for determining the input force impact – force-measuring strain gauge DST 4126 (Figure 1, pos. 4); to determine the output force impact – force-measuring strain gauge DST 4126 in the amount of 2 pcs. per each support (Figure 1, item 5).

![Figure 1. The scheme of placement of measuring instruments while testing of reinforced concrete beams B and BS samples](image)

Visualization of crack formation during short-term dynamic loading is conducted using high-speed camera Photron Fastcam SA-2 with shooting speed of 2500 shots per second.

3. Results
As a result of analysis of displacements of test samples (Figure 2) under intensive dynamic loading, it was found that application of yielding supports and the presence of thrust leads to significant decrease in the structural displacements, which, in turn, leads to decrease in the number of cracks, the depth of their propagation and their opening width, thereby increasing the durability and resilience of structures (Figure 2, Figure 3).
One of the ways to evaluate the effectiveness of yielding supports is to build the averaged deformation energy over time for the tested samples.

To obtain the averaged deformation energy over the load action interval, we multiply $F_{def}(t)$ per the averaged displacements of the structure along the length of the element:

$$E_{med}(t) = F_{def}(t) \times f_{med}(t)$$

where $E_{med}(t)$ – is the averaged deformation energy at the interval of load action; $F_{def}(t)$ – is force consumed for the sample deformation; $f_{med}(t)$ – are averaged displacements of the sample along the length at the interval of the action of above-level force impact (the average value of displacements over the time along the length of the sample).

According to the dependence given above the averaged energy diagrams (Figure 4) for the samples B and BS were built.

Analysis of energy distribution diagrams over the time shows that the structure and yielding support are deformed synchronously within the studied time range. For the structures on yielding
supports (Figure 4b) up to the time moment of ~ 15 ms the change in the averaged deformation energy of yielding support is insignificant due to the elastic deformations of yielding support. After the transition of support to the plastic stage (time more than 15 ms), a sharp increase in the averaged energy of the beam and yielding support is observed. At the same time, it can be noted that at all stages of deformation, the main part of energy of external impact is absorbed due to deformation of yielding supports (Figure 4, curves 2 and 3). Deformation energy of the beam is significantly lower than the corresponding value for yielding supports at any given time, regardless of the stage of deformation of yielding support (Figure 4, curve 4).

Quantitative estimation can be performed based on the extreme values of deformation energy. As can be seen from energy diagrams (Figure 4) the maximum value of energy $E_{med}^B = 1050 \, J$ – for the structure of B type and $E_{med}^{BS} = 1150 \, J$ – for the structure of BS type. Notably, for the sample BS in Figure 4b redistribution of energy is reflected which is accounted for the deformation of structure $E_{med,c}^{BS} = 195 \, J$, and energy accounted for the deformation of yielding support $E_{med,f}^B = 950 \, J$. Therefore, increase in the values of energy consumed for the beam deformation can be characterized by the energy coefficient $k_{E,med} = \frac{E_{med}^B}{E_{med,c}^{BS}} = \frac{1050}{195} = 5.38$, its physical meaning is that the energy applied to the structure during testing of a sample of BS-2 series was reduced by 5.38 times due to energy absorption of yielding supports, and the energy intensity coefficient of yielding support was $k_{E,flex,b} = \frac{E_{med,f}^B}{E_{med}^{BS}} = \frac{950}{1150} = 0.826$.

![Figure 4](image)

Figure 4. The diagram of averaged deformation energy over time for the samples B (a, diagram 1) and BS (b, diagram 2); the diagram of averaged deformation energy of yielding support over time for BS sample (b, diagram 3); the diagram of averaged deformation energy without taking into account crushing for BS sample (b, diagram 4)

4. Conclusion
The results of the study indicate the positive effect of yielding supports application in structures with thrust under intense dynamic loading. Based on the conducted tests, decrease in the energy consumed on deformation of the structure is observed due to energy redistribution between the structure and yielding support with equal parameters of impact loading. Reinforced concrete beam with thrust on yielding supports is more energy-intensive, which is confirmed by the coefficient $k_{E,flex,b}$ and indicates a clear reduction in energy due to the use of yielding supports.
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