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Computer simulation of yielding supports under static and short-term dynamic load

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Abstract. Dynamic impacts that became frequent lately cause large human and economic losses, and their prevention methods are not always effective and reasonable. The given research aims at studying the way of enhancing explosion safety of building structures by means of yielding supports. The paper presents results of numerical studies of strength and deformation property of yielding supports in the shape of annular tubes under static and short-term dynamic loading. The degree of influence of yielding supports was assessed taking into account three peculiar stages of deformation: elastic; elasto-plastic; and elasto-plastic with hardening. The methodology for numerical studies performance was described using finite element analysis with program software Ansys Mechanical v17.2. It was established that rigidity of yielding supports influences significantly their stress-strain state. The research determined that with the increase in deformable elements rigidity dependence between load and deformation of the support in elastic and plastic stages have linear character. Significant reduction of the dynamic response and increase in deformation time of yielding supports were observed due to increasing the plastic component. Therefore, it allows assuming on possibility of their application as supporting units in RC beams.

Introduction

Explosive impacts refer to single emergency loads; they are characterized by high intensity and short term of action, which results not only in structural failure but also in production facilities damage and human losses. The existing approaches to designing building structures resistant to explosive impacts are based on higher material consumption, which leads to increasing the cost of objects. Therefore, the alternative economically feasible and reliable approaches are needed in design of structures that are resistant to dynamic loads.

Yielding supports can be applied as one of the active means of prevention or localization of dynamic impact or reducing the intensity of dynamic loading [1-18].

Currently, research results in the field of yielding supports application for protection of buildings and structures subjected to intensive dynamic loading are fragmentary. Experimental, theoretical and experimental-theoretical research [19-22] demonstrate both positive and negative influence of yielding supports on the dynamic response of RC beams.

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This paper focuses on the numerical study of the strength and deformation property of yielding supports given as the tubes of annular section under static and short-term dynamic loading. The study aims to obtain the data on load reduction under dynamic loading resulting from the use of yielding supports. The research problem consists in impossibility of conducting experimental study that will provide comprehensive answers to the questions on the stress-strain state of yielding supports. Such situation is caused by the complex geometry of the structure under study and the peculiar features of its straining. Along with that, the solution of the mentioned objective using mathematical package requires deep knowledge in material behavior, taking into account its physical, geometrical and contact nonlinearity under static and dynamic loading.

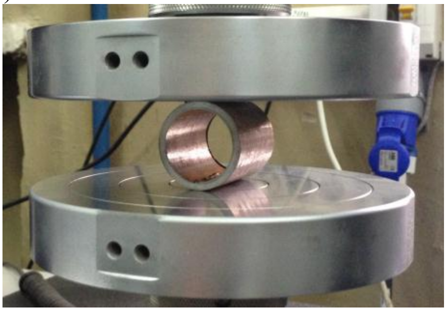
Research in [1-18] focuses on the elaboration of working models of tubes, and provide comparison of the obtained results with analytical and experimental studies. The works consider the cases of static and dynamic axial and transverse straining of samples made from different materials, including the combined ones (sandwich-tubes). The basic outcomes of the given works are presented as high convergence of the experimental and numerical studies. The present work differs from the above-mentioned ones. Those studies were conducted within the field of machinery and mechanics, while the given research is performed within the studies on increasing the explosion safety of building structures. Therefore, it focuses on variation of the rigidity of yielding supports and reduction of the system dynamic response.

1 Numerical simulation

1.1 Static loading

Program software Ansys Mechanical, v 17.2 was used for solving the set objectives. The research was conducted using finite element method as the most functional and accurate means of the stress-strain state analysis of the solid bodies complex straining processes.

a) b)



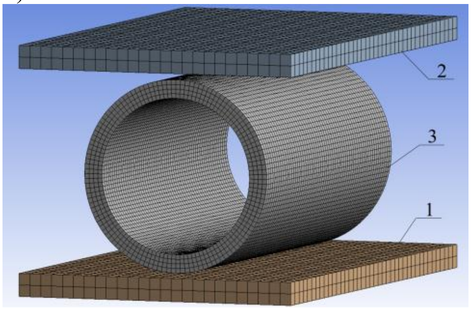


Fig. 1. The general view of yielding supports testing: field experiment (a); numerical simulation (b); 1- supporting slab; 2- force slab; 3- yielding support.

The works [8], [12, 13], [15-18] demonstrate the high degree of convergence between simulation and experimental results. Along with that, numerical studies enable to assess the state of the structure up to its failure and fragmentation of the separate parts, while experimental facilities can record the data mainly in the area of elastic strain. In case of the complex geometry, measurement of the most important data becomes impossible.

The first stage of the work included analysis of yielding supports under quasi-static loading with the constant loading velocity. The design model was idealized and formalized copy of the physical reality and it duplicated the experimental study with a large accuracy [20] (Fig. 1).

Finite element model consisted of the two slabs, one of them was supporting and motionless, the second slab served as a force slab and it had the capacity of vertical displacement. The third element of the model was yielding support. Sample spacing of the finite element mesh of the slabs was 4 mm, of the yielding support – 0.8±0.1 mm. The volume eight-node finite element SOLID185 was used as a finite element.

The analysis was performed for all the considered lengths of yielding supports in the range from 10 to 120 mm (Fig. 2). The dimensions of the solved objective depending on the length of yielding support varied from 5664 to 58464 finite elements.

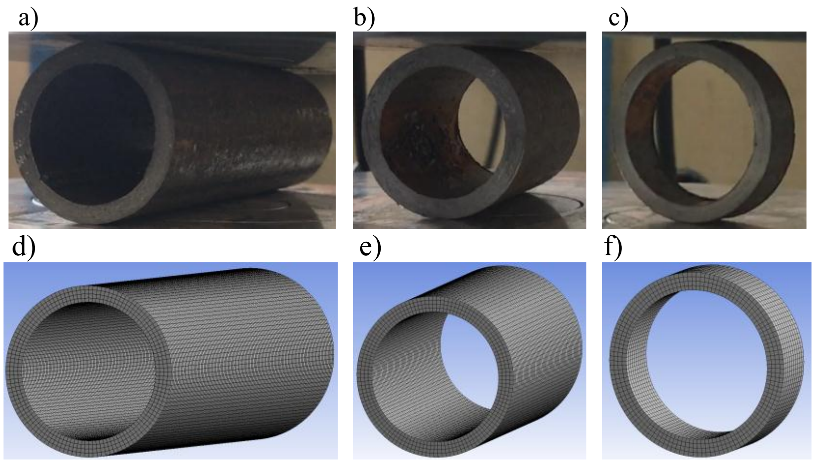


Fig. 2. The general view of yielding supports of various length: experimental studies (a,b,c); numerical finite element model (d,e,f): 120mm (a, d); 60mm (b, e); 10mm (c, f).

The work of material of yielding support was described by multilinear diagram of material straining with isotropic hardening. It was obtained by preliminary field experimental study of material under tension.

The loading of yielding support was performed by means of the given displacement of the upper slab (Fig. 1) to the distance corresponding to the inner diameter of yielding support.

1.2 Dynamic loading

Simulation of dynamic impact was conducted in the module Ansys v17.2 - explicit dynamic. The objectives were solved using Lagrangian approach to the medium motion description.

The simulation of the yielding supports operation under short-term dynamic loading was aimed at assessing the influence degree of the yielding supports on the dynamic response of the system: falling weight - yielding support - supporting slab (Fig. 3). The variable rigidity parameter in the work was changing the length of the deformable element. Cross-section and the material of yielding support were accepted in accordance with the experimental studies [20].

Within the present objective the moment of impact of the falling weight 1 on the yielding support 2 was simulated. The mass of the weight 1 corresponded to the weight used while experimental studies, which is 265 kg. For that purpose, the density of the weight was increased for each of the solved objectives.

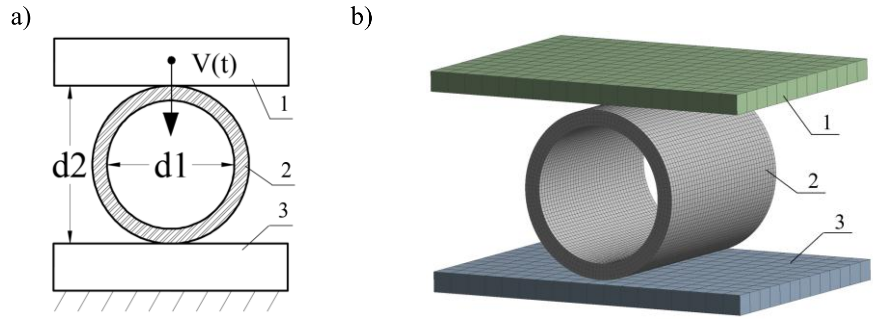


Fig. 3. Design model of the yielding support testing under short-term dynamic loading (a); general view of the finite element model (b); falling weight (1); yielding support (2); supporting slab (3); d1- inner diameter: d2-outer diameter.

The velocity of the weight 1 at the moment of impact on the yielding support 2 corresponded to the velocity of weight dropped from the height of 650 mm during experimental studies. The velocity of the weight 1 at the moment of impact on the yielding support 2 was calculated according to the dependence (1) obtained from the formulas for uniformly accelerated straight line motion and was 3.57 m/s^2.

$$S_x = \frac{V_x^2 - V_0^2}{2_{ax}}, \quad (1)$$

where: S_x- the height of falling weight (0.65 m), $V^2{}_x$- squared velocity at the impact moment of falling weight 1 and yielding support 2, $V^2{}_0$- squared initial velocity of falling weight 1 (0 m/s^2- the weight is suspended), a_x- acceleration of weight 1 (corresponds to gravity acceleration 9.81 m/s^2).

The supporting plate 3 was rigidly fixed along all degrees of freedom. Weight 1 and supporting plate 3, due to their small thickness in the model (Fig. 3 b), were accepted as completely rigid elements.

In the present work, three distinctive types of supports were considered (Fig. 9). a- completely elastic or rigid support; b- yielding support, working in elasto-plastic stage with hardening, c- yielding support, working in elasto-plastic stage.

2 Results

2.1 Static loading

Let us consider the distinctive features of yielding supports straining on the example of inserted element of annular cross-section 40 mm long (Fig. 4). As can be observed, for all the stages of yielding support work the strain pattern during field test corresponds to the strain pattern during numerical simulation.

Geometry of the studied sample during loading significantly changes its shape several times (Fig. 4) and the rigidity accordingly. Considering that fact, the model was supplemented with the option of finite displacements consideration and angular displacements after each equilibrium iteration (geometrical nonlinearity).

During straining process (Fig. 4), the yielding support interacts with the force slabs changing its design model several times. After occurrence of the plastic strain in the yielding support, the contact point with each of the force slabs is divided in two. Then, along with the load increase, the contact points distribute from the center of the support to its edges (Fig. 5). In order to consider the above-mentioned process contacting pairs were established in the model between the inserted element and the force slabs, as well as between the internal surfaces of the yielding support. The blue color in Figure 5 identifies the contact elements, which are significantly remote from the contact surface. Contact elements, which are rather close to the contacting surface, are marked with yellow color. The red color identifies contact elements interacting with the contact surface, the force slab in particular.

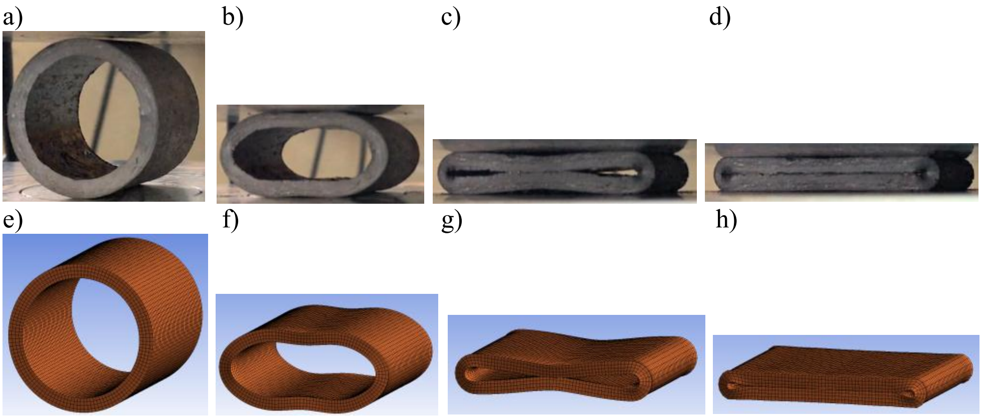


Fig. 4. Peculiar stages of yielding supports deformation: elastic (a, e); elasto-plastic (b, f); elasto-plastic with hardening (c, g, d, h).

Moreover, during yielding supports straining the contact of inner surfaces of the ring occurs (Fig. 4 c, g), which in its turn alters the simulation model one more time. Further, the internal surfaces come into contact (Fig. 4 d, h).

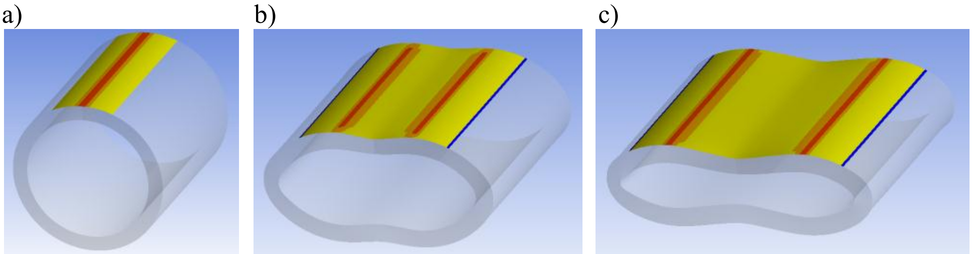


Fig. 5. Alteration of the design model of yielding support in the process of straining: one contact point with the slab (a); two contact points with the slab (b, c).

It should be noted, that during straining process distortion of the ends of yielding support occurs in the areas of plastic hinge. Thus, the contact of internal surfaces of the ring occurs not simultaneously and from the ends to the middle part (Fig. 6).

As a contact interaction interface for all contacting pairs the model of contact with friction μ=0.15 was used. This model includes the possibility to divide contacting pairs after interaction and generally can contain the areas of cohesion and sliding. Advanced Lagrangian method was used as a solution method; stepwise iteration method was used for solution of the system of linear algebraic equations. The checking of non-linear objective solution was conducted using the Newton-Raphson Method. During solving the objective of static loading of the yielding supports, the solution admitted computational error of 5%.

Along with the increase in the number of elements in the solved objective in order to provide high accuracy, the proportional increase in the number of equilibrium iterations was required. Thus, the objectives considered from 500 to 8000 iterations.

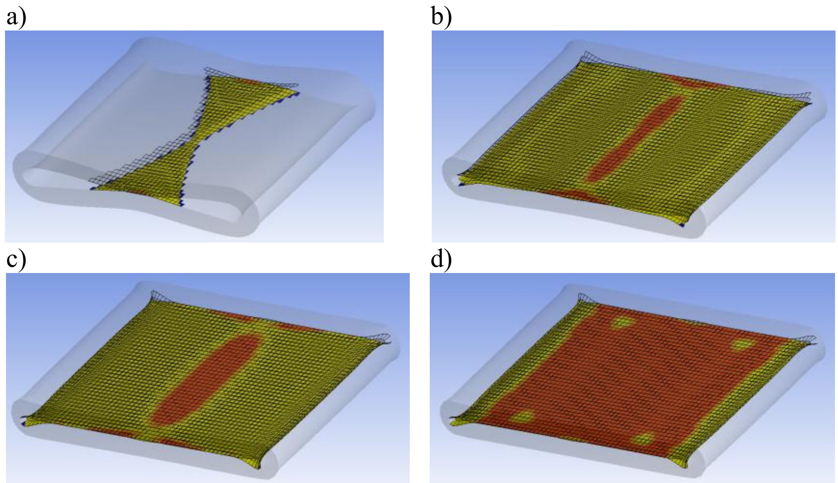


Fig. 6. Alteration in the design model of yielding support during straining: impact of contacting pairs at the edges (a); contact of internal surfaces in the mid-area (b); gradual increase of the contact spot in the middle area (c); full contact of the internal surfaces (d).

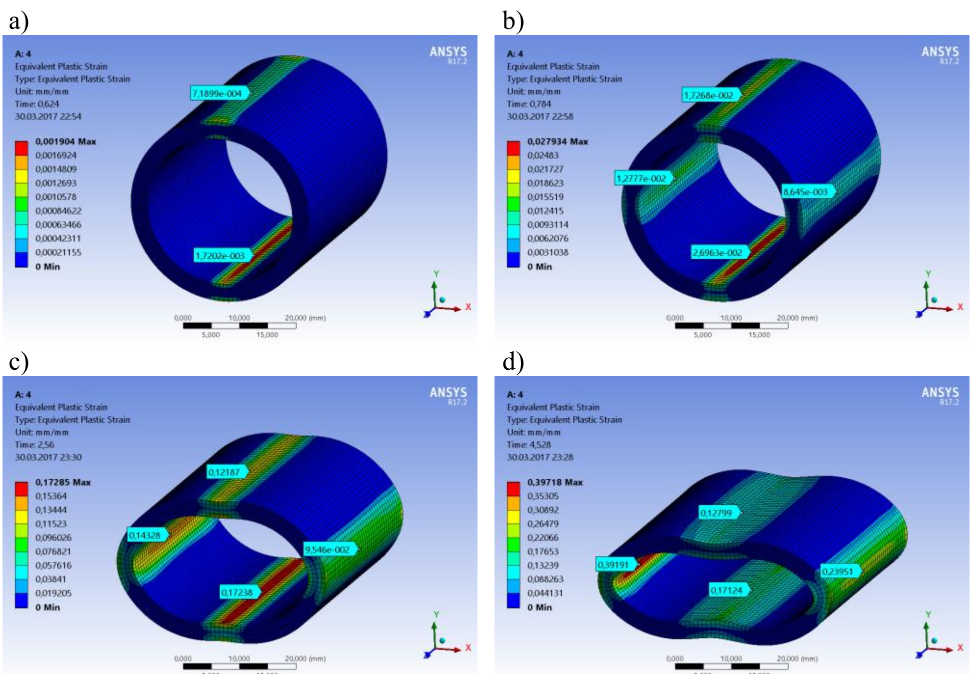


Fig. 7. Distribution pattern of the plastic strain in the yielding support.

Analysis of the results of numerical simulation demonstrated that significant straining of yielding supports occurs due to formation of plastic hinges when the stresses in the material reach the yield stress. These areas are first established in the upper and lower areas of the rings (Fig. 7*a*), and then at the lateral surfaces of the sample (Fig. 7*b*). Further straining is accompanied by the gradual growth of plastic strain and increasing the area of active straining. It should be noted that the value of relative strain at the internal lateral surface of the yielding support ε > 39% (Fig. 7*d*), which exceeds the ultimate strain of the steel 255 $\varepsilon_{s\ 255} > 26\%$.

The mentioned area of straining undergoes compressive strain and due to curvilinear geometry of the sample, these locations are marked by the materials self-hardening effect. Analysis of the results of numerical and experimental studies under quasi-static loading can be conducted based on the strain diagram of yielding supports (Fig. 8).

Figure 8 illustrates the diagrams "load-displacement" for the yielding supports 10 and 20- 120 mm long with the span of 20 mm. According to the diagram, it can be judged on the high level of accordance of the experimental and numerical results at all stages of yielding supports performance.

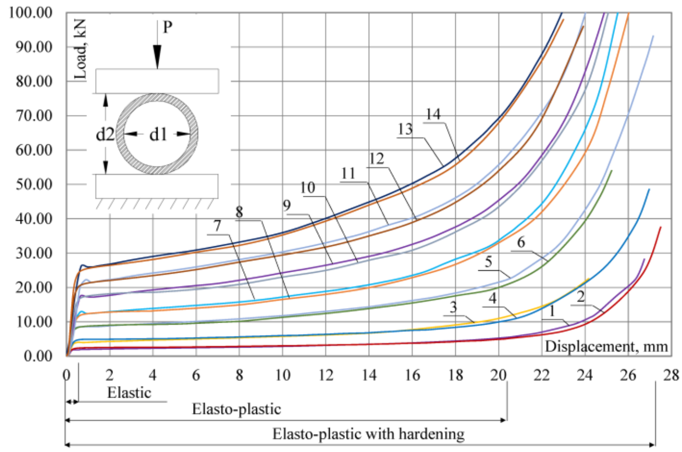


Fig. 8. The strain diagram of yielding supports of various length under numerical and experimental study; d1- inner diameter; d2- outer diameter of the yielding supports; the uneven numbers correspond to the experimental studies; the even numbers present numerical simulation. 1-2- 10 mm; 3-4- 20 mm; 5-6- 40 mm; 7-8 60 mm; 9-10-80 mm; 11-12- 100 mm; 13-14- 120 mm.

Furthermore, with the increase of the yielding supports rigidity during experimental studies the strain diagrams are marked with the "yield drop" during transition of the support work from elastic into plastic stage of hardening, however it was not observed at the diagrams of numerical simulation. This effect applies for the low-carbon steel. The occurrence of the "yield drop" is attributed to the dislocation deformation mechanism. At the initial phase, the density of dislocations is insignificant to provide larger strain degree. After reaching the upper yield stress, the intensive formation of new dislocations begins resulting in decrease of stress. Software package Ansys v 17.2 does not consider the dislocation deformation mechanisms referring to micro-structural steel composition; therefore, it leads to the absence of the "yield drop" in Figure 8.

Along with that, the local inaccuracy of the absolute value of load between the experimental and numerical result does not exceed 3.5 % and does not change significantly the general strain pattern of yielding support within the solution of the given objective.

2.1 Dynamic loading

The degree of influence of the support rigidity can be evaluated from the diagram (Fig. 13). The first case (Fig. 9*a*) presents the support, which possesses the properties of low-carbon steel, which strains according to the Hooke's law. It means that its work does not imply plastic strain occurrence. This support can be conventionally considered as a rigid as the relative strain in it under dynamic loading will be changed according to the linear law with the constant deformation modulus corresponding to the steel elasticity modulus.

a) b) c)

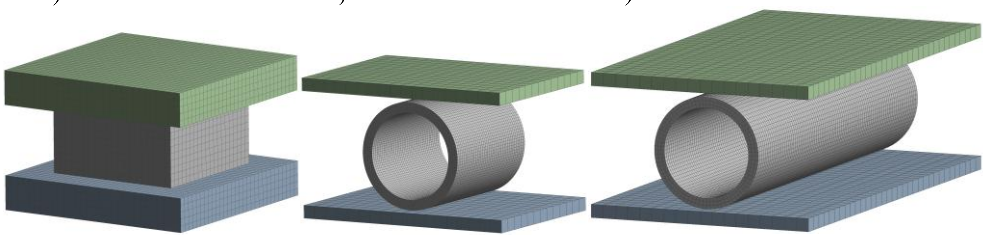


Fig. 9. Computational models of yielding support under short-term dynamic loading; totally elastic (rigid) support (a); yielding support, working in elasto-plastic stage with hardening (b); yielding supports working in elasto-plastic stage (c, d).

The support working in elasto-plastic with hardening stage (Fig. 9*b*) is characterized by the plastic straining with smooth increase in the dynamic response up to the moment when the internal surfaces of the supports contact (Fig. 10) and (Fig. 13*b*, point A). After that sharp increase in the value of dynamic response occurs.

Supports working in elasto-plastic stage (Fig. 9*c*), (Fig. 13 3, 4), depending on their rigidity can have different dynamic response diagrams. Along with the increase in plastic component of such supports increase in time of response occurs. Thus, for instance for the support 120 mm long (Fig. 13 4), compared to the support 1600 mm long (Fig. 13 3), the time of dynamic resistance increased by 2.66 times, which testifies on more plastic work of the first one. Moreover, the support of the larger length does not deplete the whole potential of its plastic properties (Fig. 11), while the support of the less length almost come into contact by the internal surfaces of the ring (Fig. 12). The decrease in the maximum value of dynamic response should be noted (Fig. 13 3, 4) from 407 kN corresponding to the support 1600 mm long to 288 kN for the support 120 mm long which makes 29.2 %.

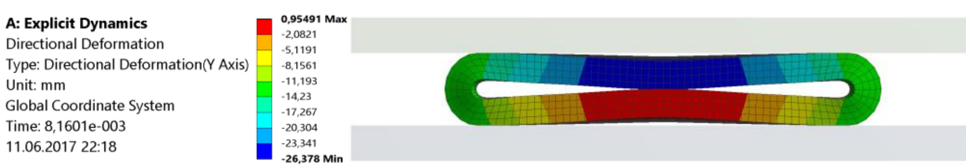


Fig. 10. The overall scheme of the support straining, working in elasto-plastic with hardening stage, the moment of transition of the support into hardening stage point A (Fig. 14*b*).

Having compared the support work in elasto-plastic stage (Fig. 13 3, 4) and the support work in hardening stage (Fig. 13 2), the reduction of the system dynamic response by 6.4 times was observed (Fig. 13).

Conducting the analysis of yielding supports work (Fig. 13 2-4) with totally elastic (rigid) support (Fig. 13 1), a significant reduction in the system dynamic response was revealed, thus, for instance for the elasto-plastic support (Fig. 13 4), compared to the rigid support (Fig. 13 1) the reduction was 23.4 times, and for the elasto-plastic with hardening support it was 6.62 times. Along with that, the increase in the time of dynamic response for yielding supports compared to the rigid ones should be specified (Fig. 13). The time of straining for rigid supports was 0.0005 sec, while for the supports working in the hardening stage it was 0.009, and for elasto-plastic it was 0.012, which is 18 and 24 times more than for the rigid supports accordingly.

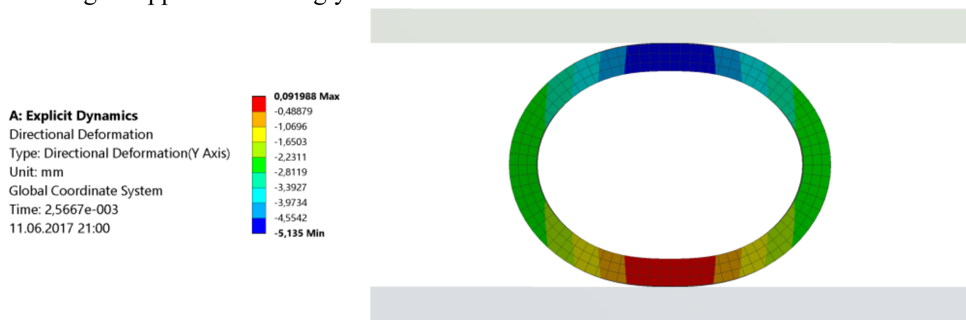


Fig. 11. The general strain pattern of the support working in elasto-plastic stage (the length of the support 1600 mm).

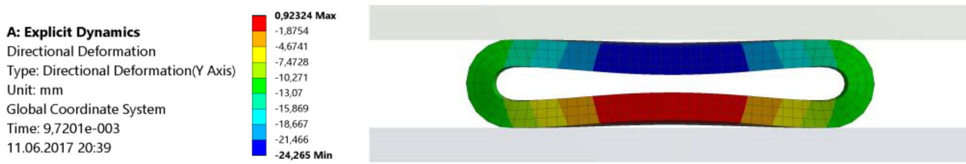


Fig. 12. The general strain pattern of the support working in elasto-plastic stage (the length of the support 120 mm).

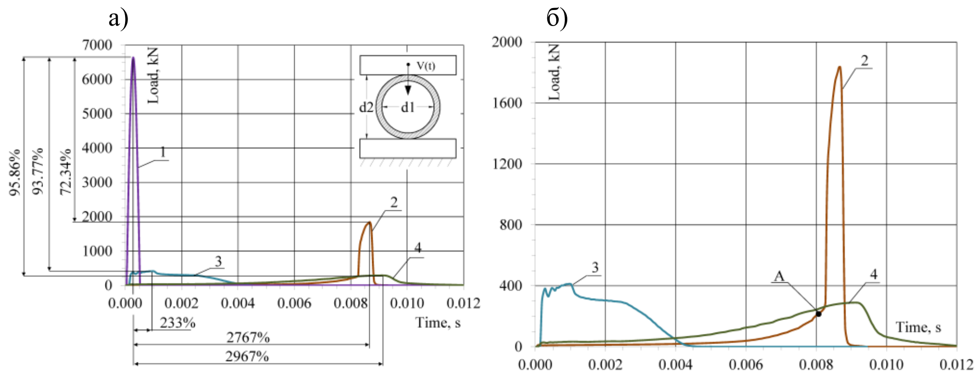


Fig. 13. Diagram of changing in the dynamic response of the supports depending on their rigidity; totally elastic (rigid) support (1); yielding support, working in elasto-plastic with hardening stage (2); the moment of transition of yielding support into the hardening stage (A); yielding supports working in elasto-plastic stage (3, 4).

Conclusions

The findings of the present research enable to conclude on the high efficiency degree of the yielding supports in the shape of annular inserted elements subjected to short-term dynamic loading compared to traditional totally elastic (rigid) supports. The required effect is reached due to the peculiarities of plastic straining of the annular section and increase in the time of dynamic straining. Therefore, the obtained results enable to judge on the possibility of yielding supports application aimed at the increase in the dynamic strength of RC beams.

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