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Analysis of reinforced concrete space frame deformation with composite sections elements

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Abstract. The results of experimental studies and numerical analysis of reinforced concrete space fragment frame high-rise building to the limit and beyond. The calculation of these construction systems are made in a constructive and physically nonlinear formulation. As a design uses two-level scheme, which is used to calculate the specified design load in the algorithm at the first stage, and in the second stage for the beyond design basis impact caused by a sudden emergency shutdown of one of the frame struts. The features of composite beams deformation, as part of the structural system before and after beyond design basis exposure, cause a sudden structural adjustment the structural system. We obtained the satisfactory agreement of calculation results by the proposed algorithm to analyze the deformation of physically and structurally nonlinear reinforced concrete space frames with structures' test result.

1. Introduction

The problems solution of the buildings structural safety always remained in the center of attention in the design of buildings and structures in terms of impacts increasing range on structures. Currently, there is a new class of problems associated with the survivability of buildings and structures and their protection from the progressive collapse in the conditions of special emergency actions [1]. The formulation and solution of this direction individual tasks in the last decade in Russia and abroad was gained attention in number studies of authors, e.g. in [2-14]. However, for the most part, these and other works are staged and dedicated mainly to the creation of theoretical models of structures-limit state deformation. At the same time, the rating generated by analysis models for the solution of structurally, physically and geometrically nonlinear problems, and the more methods of structures protection from progressive collapse is hardly possible without a thorough experimental validation of new design parameters used in the proposed analysis models. In this regard, the purpose of this research was the experimental study of deformation features, cracking of the reinforced concrete fragment structure of frame high-rise building with cross-beams of composite sections in the process of the design loads loading and design basis accidental impact.

In previously published works [15-16], the design of prototypes, testing procedures and experimental data on the movements, patterns of crack formation and failure of experimental designs in the process of a project load loading and after a sudden shutdown of a fragment pillar.

2. Design of prototypes

Tests were conducted for a fragment of a reinforced concrete frame and core frame of the building with beams of composite sections (Figure 1).

Design experienced spatial reinforced concrete frame consisted of four cross-pins located reinforced concrete composite sections, integrally connected and supported at one end on a concrete stand, and the other on the metal rack.

Figure 1. General view of the test reinforced concrete space frame.

This stand is designed in such a way that if any given project loads it may be instantly disengaged from the work of experienced construction space frame.

The frame crossbars are made in the composite rectangular cross-section form of two elements in height: the upper 80 mm height of concrete B15, and the lower 60 mm of concrete B35. Section width of each crossbar element adopted 60 mm Reinforcement beams made of flat knitted, welded frames with longitudinal reinforcement for the bottom rods with a diameter of 8 mm class A400, the upper rods of smooth wire with a diameter of 2 mm of St.3. Shear reinforcement is projected from the reinforcing wire with a diameter of 1.5 mm with a step of 80 mm and mounted in the supporting zones in the thirds of the each span bolt. Concreting of the bolts was performed in two stages. In the first phase the concrete form of the lower element was laid in the formwork so that it acted as shear reinforcement of the composite frame bolts. Then a thin layer of a flowable material was laid, separating the lower and upper concrete elements of the crossbar and then concreted the top element of the bolt. At the same shear reinforcement frame bolt crossed the seam of the contact elements of component pins. The pitch and diameter of the transverse reinforcement and the seam construction of the contact between the lower and upper elements of the composite pins were chosen so that the initial shear modulus of the contact, G0, is calculated according to [17], was ~ 1000 kPa.

Rack frame is designed from concrete seam of B35 class with a solid cross section of 60x140 mm, reinforced with knitted flat frame, with symmetrical longitudinal reinforcement of diameter 8 mm class A400 and cross fittings, wire diameter 2 mm, St.3.

3. Design of the experimental fragment

The experimental design calculation of the space frame is made in two stages, using two-level calculation scheme (Figure 2) and a specially developed algorithm. The first stage was experimental design calculation of spatial frame according to the primary design scheme (Figure 2 (a)) to test the effect of concentrated loads P1, is applied to composite beams, with spans L1 and the load P2 is applied to one of the span L2 girders. After determining effort: bending and tensional moments (M, T) and transverse force Q in beams of larger span experiencing bending with torsion from the set of test loads with step-iterative loading of a fragment to the level of a given design load, the design of composite beams was calculated using the design scheme of the second level, representing a finite-element spatial model of the compound structure and bolt the rack frame (Figure 2 (b)). The results of this calculation were determined by forces in the reinforcement, compressed concrete, the concrete height of the compressed zone, cracking effort and the widths of cracks in each loading step of the fragment. The effort and rigidity of the pins sections specified by iterations at a given load level, a simulation of the cracks in the stretched concrete was carried out using the methodology of [18].

In the second stage of calculation using so-called secondary design diagram schema obtained from the primary design scheme by instantly removing the b-pillar of the frame, which in the secondary circuit was simulated by the application of the effort force in the crack in the primary design scheme to it, but with the opposite sign. This model and studies are shown [9], it allows to define dynamic in the elements of the considered frame and truss structural systems on the first half-wave oscillations of the system after the above-mentioned structural adjustment (sudden removal of rack).

It obtained by the secondary design scheme of efforts in the elements, frame was used in the individual elements calculation of the frame according to the scheme of the second level (Figure 2 (b)). Composite beams in this scheme, and the contact seam of two beams, as in the primary design scheme, modeled volumetric finite elements that take into account the shift in the contact zone of component pins elements comprising the concrete adjacent on both sides to the contact seam, and the transverse reinforcing bars nailing [17]. The calculation result of the bolt by the described algorithm defined stress and strain in the compressed concrete in the contact zone of two composite cross-section elements of the pins, the inception and opening up of new cracks at the stretched areas of the structure after a sudden structural adjustment.

(a) (b)

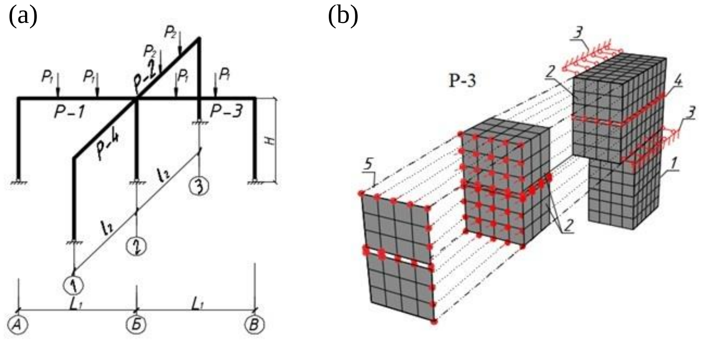


Figure 2. Schematic diagrams of the spatial frame of the first (a) level, the second (b) level: 1, 2 - volumetric FE of the column and the composite bolt, 3-FE bonds to prevent turn of the crossbar, 4 - connection of tension, compression, shear, 5 - Combining the movements between the rigid plate and the volume elements.

4. Experienced analysis and calculation of parameters of deformation of reinforced concrete space frame

Experimental and calculated dependence "moment-curvature" for the middle cross section of the composite pins of P-3 test fragment frame construction allow to note the following (Figure 3). The first cracks in the design of composite pins (P-3) opening width up to 0.05 mm was recorded in upper fibers zone bolt to the stand-3 to 10 stage of loading. At of 13.5 kN (12 stage) load in the span of the crossbar R-3 on the lower fibers of the stretched zone of the composite pins lower element the first cracks with the opening of 0.05-0.07 mm was formed (Figure 3, the value of Mcrc1). With increasing loads up to 18 kN (17 stage) opening width of these cracks increased, and the cracks developed up to the height of the bolt cross section.

After beyond design basis effects, the crack has received additional disclosure in sudden shutdown form of a frame b-pillar. In particular, cracks at the bottom element of the considered cross-section of the composite pins was increased to 0.5 mm, and in area of bolts-pillar-3 - 2.0 mm. this effect has also formed new cracks in the lower zone, the upper part of the considered cross-section of a composite bolt R-3, opening width at this stage 0.1-0.3 mm (Figure 3, the value of M_{crc2}). In addition, after beyond design basis effects in Rigelm composite R-3 formed longitudinal crack along the seam of contact between two concrete composite beams, with openings up to 1.6 mm (Figure 5).

In the presented graph theoretical dependence "moment-curvature" (see curve 1 in Figure 3) you can trace the beginning of the normal cracks formation in the section under the bolt R-3 on the lower face of the lower element of the composite pins (M_{crc1}) and the bottom face of the top element (M_{crc2}) typical fractures on the curve deformation. The theoretical values of the cracking marked points were as follows: 1) for normal cracks in the lower element of the composite pins R-3 to beyond design basis impact Mcrc1=0.48-0.61 kN*m.

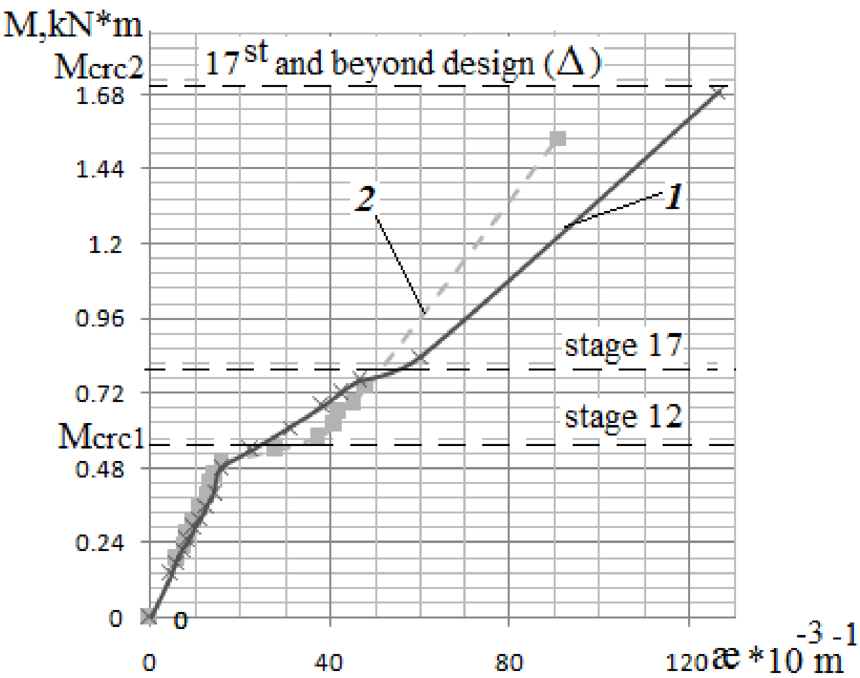
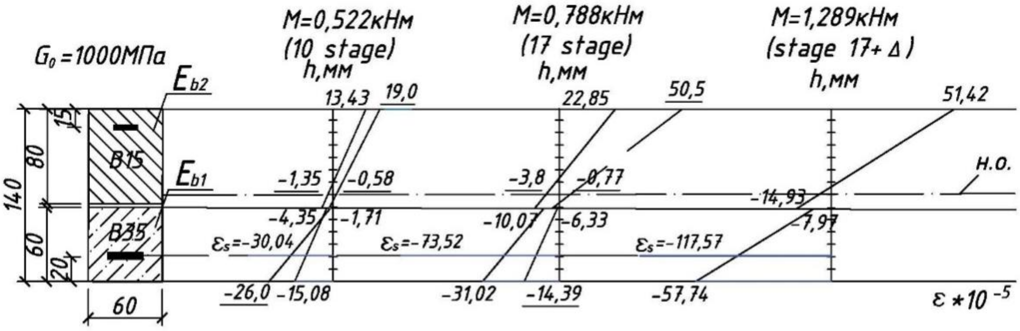


Figure 3. Dependence of "M-æ" in the average cross-section of the crossbar P-3: 1, 2 - calculation and experiment, respectively.

By processing results of calculated and experimental data was constructed plots of the relative distribution of height deformations along the bolt cross section for the section at the extreme of the support bolt (Figure 4 (a)) and cross section in the center column of the fragment (Figure 4 (b)).

Analyzing the obtained theoretical and experimental data about the distribution of concrete relative deformation at the height of the element section, it is possible to note the presence of a marked strain gradient on the border of contact seam of two concrete composite sections. Consequently, the area of two composite pins elements contact had the high deformability and the distribution of deformations along the height of the bolt cross section took place according to the beam composite sections deformation [17]. It is pertinent to note that the dashed lines in Figure 4 abstractly shows a distribution plot of average values of concrete deformations in stretched areas of the pins in the regions between cracks. Here the bold line shows the average deformation of tensile reinforcement in the cross sections.

(a)



(b)

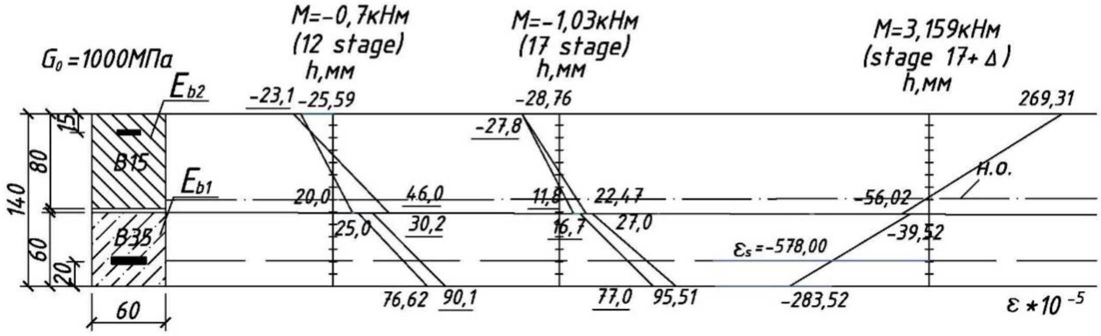


Figure 4. Diagrams of the concrete relative deformations distribution and reinforcement in the composite crossbar P-3 of the spatial reinforced concrete frame with the shear modulus of the contact between the elements at G_0 = 103 MPa: (a) - at the extreme support of the crossbar; (b) at the central post of the crossbar; 1,2 - respectively, the calculated and experimental.

Analyzing the widths noted above are typical of cracks in the design loading and the considered beyond design basis impact (Δ) because of the Central support fragment the following may be noted (Figure 5). Changing the experimental values of the cracks widths in the stretched zone of the composite pins lower element in the process of the design load loaded (the 12-th and 17-th stages) were non-linear. The calculated (1) and experimental (2) values of cracks widths had satisfactory quantitative agreement between them (table 1). The increment of the considered cracks widths in the stretched zone of the composite pins lower element after the beyond design basis impact of a specific calculation using existing standards [19, 20] (Figure 5, plot graphs 1 and 2 between the stage 17 and the stage 17 Δ R) are also in satisfactory agreement among themselves. This implies proposed design scheme and algorithm design analysis of reinforced concrete space frame in limit state rather strictly models the deformation parameters of such structures under the considered structural rearrangements caused by the sudden shutdown of a frame bearing element.

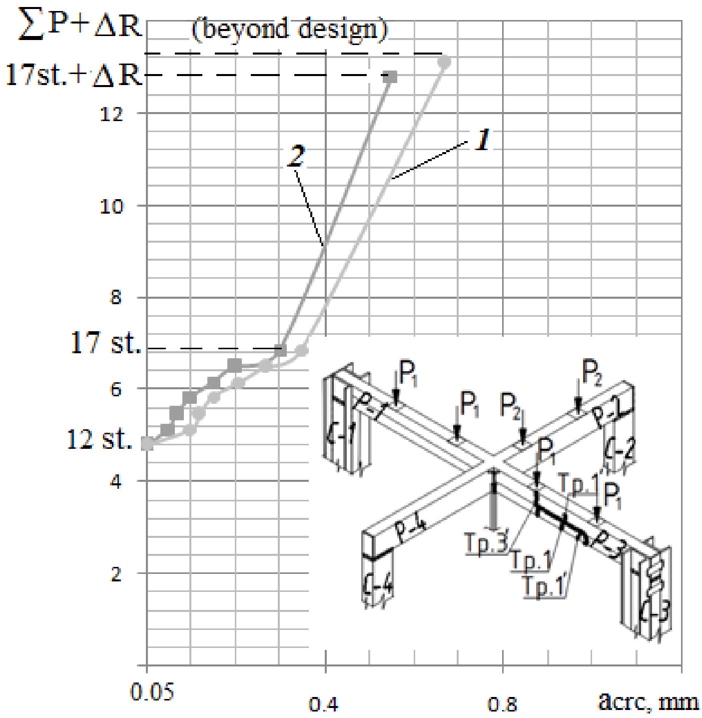


Figure 5. Dependence "load-width of crack opening" for the spatial frame: 1 - calculated, 2 - experimental in the middle of the span of the composite crossbar P-3.

Table 1. The width of crack opening in the structural system before and after the design-basis design.

Loading number	Project load, kN		Opening width of cracks a_{crc}, mm in the middle of span P-3	
	P_1	P_2	experimental	calculated
10	4.44	3.82	-	-
11	4.8	4.12	-	-
12	5.14	4.4	0.05	0.1
13	5.48	4.7	0.07	0.12
14	5.84	5.0	0.1	0.15
15	6.16	5.3	0.15	0.21
16	6.5	5.5	0.2	0.27
17	6.86	5.9	0.25	0.35
Dynamical loading	$\sum P_1 + P_2 + \Delta R$		0.55	0.65

The destruction of the frame experimental fragment was characterized by a significant increase in deflections of the frame girders (1/56 span), the disclosure of normal cracks in composite beams, as in the span and at the support S-3, as well as the destruction of the weld contact between the elements of the bolt component section R-3. The opening of the longitudinal cracks in the weld contact reached 1.6 mm. a Significant influence of dynamic effect on the fracture toughness of the rest of the structural system destroyed elements experienced the frame is supported by the fact that residual crack widths in the considered composite Rigel R-3 and other elements of the frame are much greater than the opening width prior to the application of beyond design basis loads (see Table 1).

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5. Conclusions

The analysis and comparison of calculation results and experimental test data model the spatial fragment of frame-and-rod construction system - a fragment of reinforced concrete frame high-rise building with cross-bars of composite sections have allowed establishing its deformation features, crack formation and failure in the ultimate limit state and by the rapid structural adjustment of the considered structural system.

The resulting increment of strain and the opening cracks width in the cross sections of composite girders after the sudden inclusion of a vertical support member (rack frame), confirmed the effectiveness of the proposed algorithm of such systems calculation taking into account the structural and physical nonlinearity, shear deformation along the contact pins seam of composite sections and dynamic caused by the suddenness of structural adjustment the structural system.

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