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OSNOVNE PRETPOSTAVKE ZA ISTRAŽIVANJE STANJA NAPREZANJA-DEFORMACIJA OŠTEĆENIH ARMIRANOBETONSKIH STUPOVA KRUŽNOG PRESJEKA

BASIC ASSUMPTIONS FOR THE RESEARCH OF STRESS-DEFORMATION STATE OF DAMAGED REINFORCED CONCRETE COLUMNS OF CIRCULAR CROSS-SECTION

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Pregledni rad

Sažetak: *Na objektima izgrađenim u prošlom stoljeću jasno su vidljivi određeni tipovi oštećenja kod kojih je razvidno da su nastali zbog kombinacije određenih faktora: dugotrajne eksploatacije konstrukcije, dugotrajnog kontinuiranog opterećenja, dinamičkih i na kraju kemijskih utjecaja. Analizirajući sve moguće uzroke oštećenja, u članku je detaljno razrađena klasifikacija oštećenja ab konstrukcija. Analiziran je armiranobetonski stup kao tipičan, strukturni element mnogo puta korišten u konstrukciji. Pregledom literature i raznih eksperimentalnih istraživanja u posljednjih 80-ak godina izdvojen je jedinstven tip oštećenja eksperimentalnih modela koji se nedvosmisleno poklapa s oštećenjima nastalih tijekom eksploatacije stupa. Dan je prijedlog modela ispitivanja oštećenih ab stupova te su analizirani osnovni parametri koji će dovesti do sloma elementa tijekom ispitivanja.*

Ključne riječi: *Armiranobetonski stup, naprezanje, deformacija, oštećenje, „klin“, lokalno izvijanje.*

Review article

Abstract: *Certain types of damage are clearly visible on the buildings built in the last century – it is evident that they have been caused by a combination of certain factors: long-term use of the building, long-term continuous load, dynamic and chemical influences. By analyzing all the possible causes of the damage, this article elaborates in detail the damage classification of reinforced concrete structures. The RC column is analyzed as a typical, structural element, used in construction many times. Reviewing the literature and a variety of experimental studies within the previous 80 years, a unique type of damage of experimental models is separated. This clearly corresponds with damages formed during the exploitation of a column. The proposed model for experimental study of damaged RC columns is given. Basic parameters that will lead to the collapse of the element during the test are analyzed.*

Key words: *Reinforced concrete column, stress, deformation, damage, "wedge", local buckling.*

1. INTRODUCTION

Nowadays, the attention of the construction industry is focused on high-performance construction materials. This refers primarily to the high strength concrete, because concrete is now (still) leading and most applicable construction material. Its increased use in the last 20 years is primarily noticed in columns because of their high bearing capacity in compression (especially in high-rise buildings). However, the question is set: what about the constructions built of normal strength concrete, their structural elements, resistance, durability, and their bearing capacity? Certain types of damage are clearly visible on the buildings built in the last century. It is evident that they have been caused by a combination of certain factors: long-term use of the building, long-term continuous load, dynamic and, finally, chemical influence. The main question with these kinds of damaged structural parts of the structure is whether and for how long can the structural element still perform its (designed) bearing role.

Figure 1. Examples of types of damage noticed in old buildings

Figure 2. Repair of column damage caused by long-term exploitation

2. DAMAGE CLASSIFICATION OF CONCRETE STRUCTURES

Various authors, technical committees and regulations have dealt with damage classification through history. As for the rules, EUROCODE 2 [1] and Derzhavni budiveljni normi Ukrajini (DBN) [2] prescribe restrictions in the design area of structure (due to the temperature effect, creep and shrinkage of concrete, long-term compressive stress, maximum crack). Regulations in other European countries are written in a similar way.

The RILEM (International Union of Laboratories and Experts in Construction Materials, System and Structures) technical committee DCC-104 in 1991, after a three-year work brought out a state-of-the-art report on the classification of damage in concrete structures [3]. In summary, it can be said that most of the damage to concrete structures originates due to the generally poor design (design phase of construction), poor technology and poor quality of construction materials (construction phase), overloading of the structure (exploitation phase, but also the design!) and from a variety of atmospheric and chemical influences. The actual classification can be illustrated by the following picture:

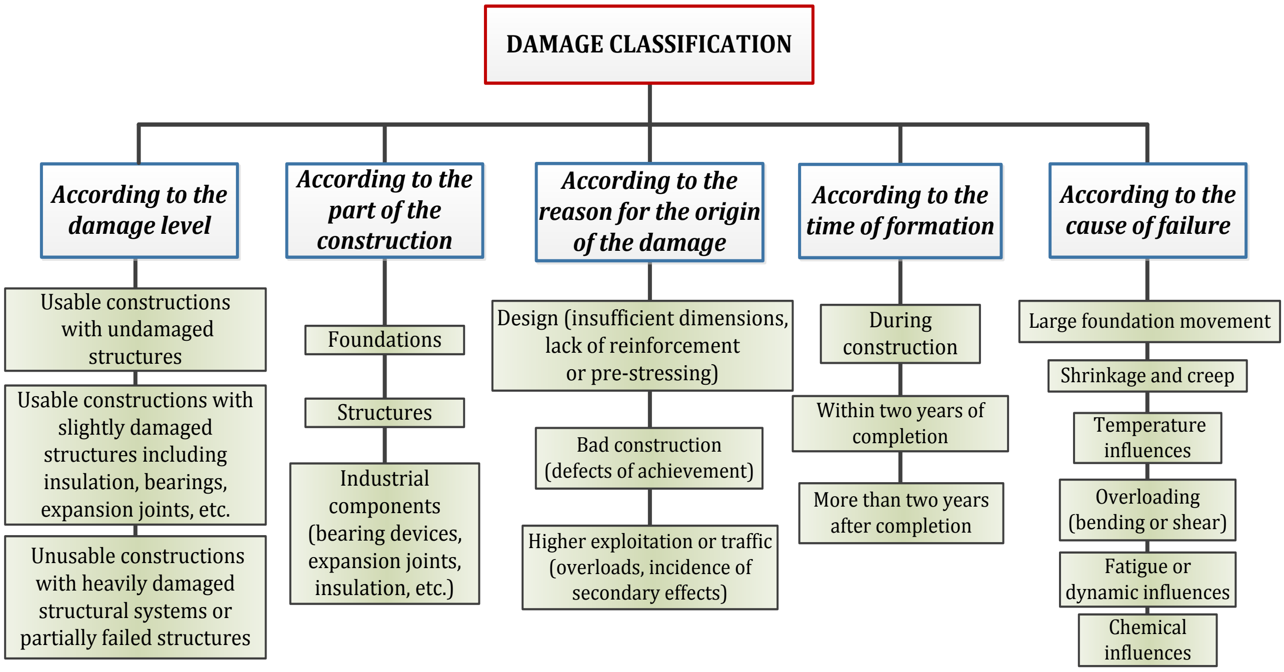


Figure 3. Damage classification scheme

The basic characteristic of these types of damage is the appearance of different types of cracks. Further detailed distribution (new classification) can be defined only on the basis of causes and types of cracks. Dobromislov [4], Ahmetzjanov [5] and Gabrushenko [6] have dealt in detail with the aforementioned in their work. Detailed historical review and experimental analysis of fracture mechanics with emphasis on the occurrence and development of cracks was given by Østergaard [7] in his dissertation paper. Karpenko [8], Saouma [9], Buyukozturk [10], Surendra and Chengsheng [11] dealt with detailed fracture mechanics of concrete in their work. If we look at the cause of the damage, the most interesting thing is the appearance of cracks (a manifestation of damage) as a result of the load, i.e. overload. If this is connected to the durability factor of the construction, then we need to look at the time of damage formation – that is the time when it became clear that the structure began to yield (formation of cracks). Considering this, the formation of cracks can be divided into:

a) overloading without permanent deformation (short-term overloading in the elastic area of stress),
b) overloading with permanent deformation (deformation over the elastic limit).

Calculation methods according to the limit states are based on the analysis of bearing capacity of materials. It is clear that the calculated bearing capacity is only theoretical state because it is insured with more safety factors. In fact, we can say that the theoretical strength of concrete is 55-65%.

3. RC COLUMNS SUBJECTED TO AXIAL FORCE

Column is a typical, simple structural element, used in construction many times. Its influence on the ductility and overall performance of the entire structure is significant. In recent decades, many authors have conducted various research on RC columns. In most cases, the research was focused on the ultimate bearing capacity of element, the behavior of the column subjected to different types of stress (compressive, tensile, shear, and combinations), and the role and limitations of reinforcement due to appearance of cracks and the very bearing capacity of the element. Special attention is contributed to high-strength concrete columns research (≥ 50 N/mm2) due to the increasing demands of durability and endurance, especially in the unstable seismic areas.

Most of the examined axially loaded columns are analyzed to the point of breaking stress (breaking of the sample) with monitoring the appearance and spread of cracks at certain cyclic load until the complete rupture. Here we can mention the following authors: Stavrov Г. H. et al. [12], Zhirenkov A. H. et al. [13], Sheikh A.S.et al. [14], Bryant A.H. et al. [15], Abolitz A.L. [16], Matamoros A.B. et al. [17], Gu S. [18], while the first studies on concentrically loaded columns started in the '30s of the last century with Richart et al. (1928, 1929). The aim of the first studies on concrete columns was to suggest a good analytical model to describe the stress-strain relationship. The main variables taken into account were the dimensions, concrete strength and the amount and spacing of transverse reinforcement (stirrups).

The type of damage of the tested samples after their fracture was particularly noted during the review of the research. It has been noticed that the fracture is locally oriented, of certain "wedge" type/appearance, that it is placed on or around the middle of the column, and that the length of the damaged part is 20-30% of the total column length. This is particularly noticeable in research by Němeček J. et al. [19], Rabie M. [20] (Figure 4 and 5).

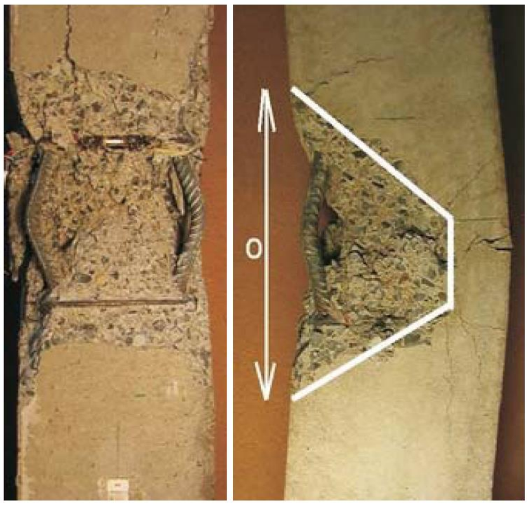


Figure 4. Characteristic damage of columns subjected to axial force (J. Němeček et al.)

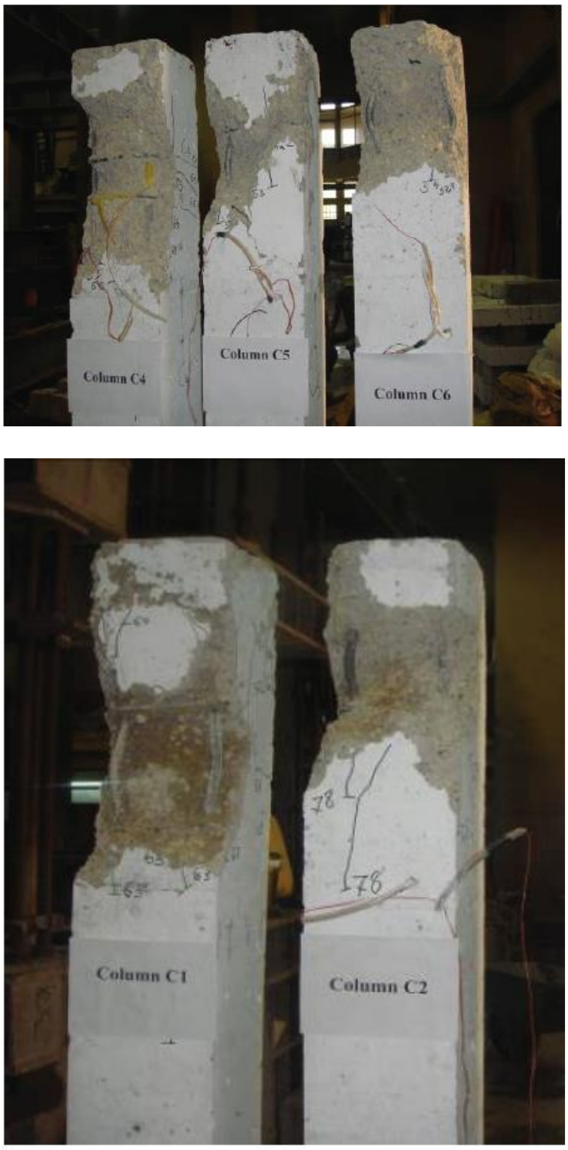


Figure 5. Characteristic damage of columns subjected to axial force. Columns damaged in the upper zone because that part of the column was made from poor concrete (Rabi M.)

When we compare this pattern of damage to the samples from the beginning of the article which were noticed in the buildings from the previous century (age 40 and over), the similarity is clear and unambiguous. We can conclude that the columns of the buildings suffered not only from the deterioration of the structure (and everything that this cause carries), but also from long-term or short-term loads. The basic features of this type of damage are the following:

- they appear near the center of the column,
- identical "wedge" shape,
- damage depth is between R / 2 and R (radius),
- height of the damaged section is between 20-30% of the total column height,
- strong deformation of reinforcing bars in the damaged part (though still plastic).

However, unlike the examined samples in literature, damaged columns that were noticed in practice still continue to bear – that is, with all clearly visible structural damage, they still did not reach their yield point, i.e. limit strain! The following important questions are set:

- What is (still) their bearing capacity?
- What is their lifespan under the constant load?
- Is the whole structure critically endangered?
- Is the recovery (repair) of columns possible and cost-effective?

4. PROPOSED RESEARCH MODEL OF DAMAGED RC COLUMNS

Studies of these kind of damaged elements and their behavior under load are quite rare. It was the main theme in the work of Klimenko E.V. Klimenko E.B. [21-26], Zabegaev A.B. [22] – analyzing factors during stress load that influence the most the bearing capacity of the damaged element. Dimensions of the damaged zone were observed, as well as the position and eccentricity of the force during the test.

With the new set-up concept damaged reinforced concrete columns of circular cross-section will be tested by monitoring these three basic factors x_i:

- depth of the damage b (x_1)
- force eccentricity e_0 (x_2)
- the angle of force position in relation to the main axis of the cross section γ (x_3)

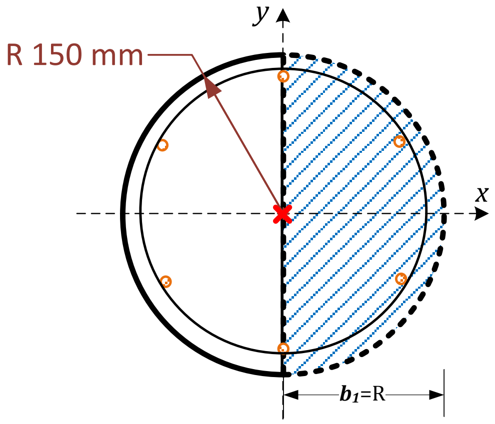
Each of the main factors will be tested in three separate cases (-1, 0, +1), so that the planning matrix looks like this:

Table 1. Planning matrix's basic elements

	x_1	x_2	x_3
-1	*0*	*0*	0
0	$R/2$	$R/2$	45°
+1	*R*	*R*	90°

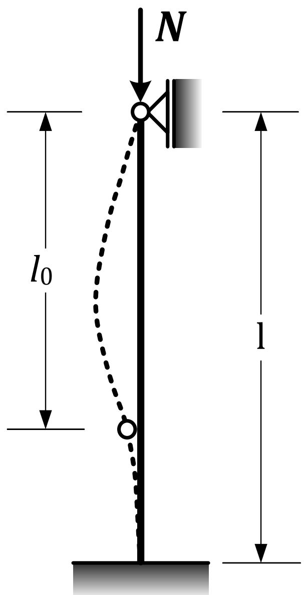
Figure 6 shows the geometry of the model chosen for the research with one possible positional plan of three basic factors x_i.

Figure 7 shows the selected type of boundary conditions on the basis of which we calculate the slenderness of the column.



reinforcement bar Φ12 (6Φ12 ≅ 6.79 cm^2)
concrete C25/30
reinforcement class B500B
coating $c = 3cm$

Figure 6. Basic geometric characteristics of the proposed model



$$l_0 = \frac{l}{\sqrt{2}} \cong 0.707 \cdot l$$

Figure 7. Boundary conditions and buckling length

According to current Ukrainian and European standards (EC-2, EN, DBN) [1, 2] columns are considered short if the increasing of bending moment given by the first order theory due to deformation is not greater than 10%. If so, their design by the second order theory is not necessary. The requirement is:

$$\lambda \leq 25(\omega \cdot 0.9)\left(2 - \frac{M_{01}}{M_{02}}\right) \quad (1)$$

where:

ω	$\frac{A_s \cdot f_{yd}}{A_c \cdot f_{cd}}$; if A_s is unknown, ω may be taken as *0.1;*
A_s	total area of reinforcement in cross-section
λ	slenderness ratio (slenderness)
M_{01}, M_{02}	first order end moments in braced members - if both moments are zero (*0*), the ratio should be taken as *1.0.*

Slenderness calculation for the column of length *l=3.0m*:

$$\lambda = \frac{l_0}{i} \leq \lambda_{max} \qquad (2)$$

where:

l_0	effective length of the element
i	$i = \sqrt{\frac{I}{A_c}}$ radius of gyration of the concrete section without cracks

Substituting the basic parameters of the selected element with length l=*3.0 m* slenderness of the element is *28.0* which is less than $\lambda_{max} = 28.75$.

Thus, we conclude that the column provided for analysis (3 m height) has slenderness lower than the limited one. Therefore, design by the second order theory is not required and such column can be considered as short. We can conclude that our test patterns can be of less length than the representative one (*l = 3.0 m*) because the deformation caused by bending can be neglected. Due to the high rigidity of the element to buckling, critical force will not be able to be achieved, so the problem of bearing capacity will be the one of boundary stresses. The collapse of the column will be reached by limit force $N_{Rd} \equiv N_{Sd}$.

As stated earlier, one of the features of these types of damage is local deformation of reinforcement bar, namely local buckling reinforcement due to loss of element bearing capacity (Figure 8a).

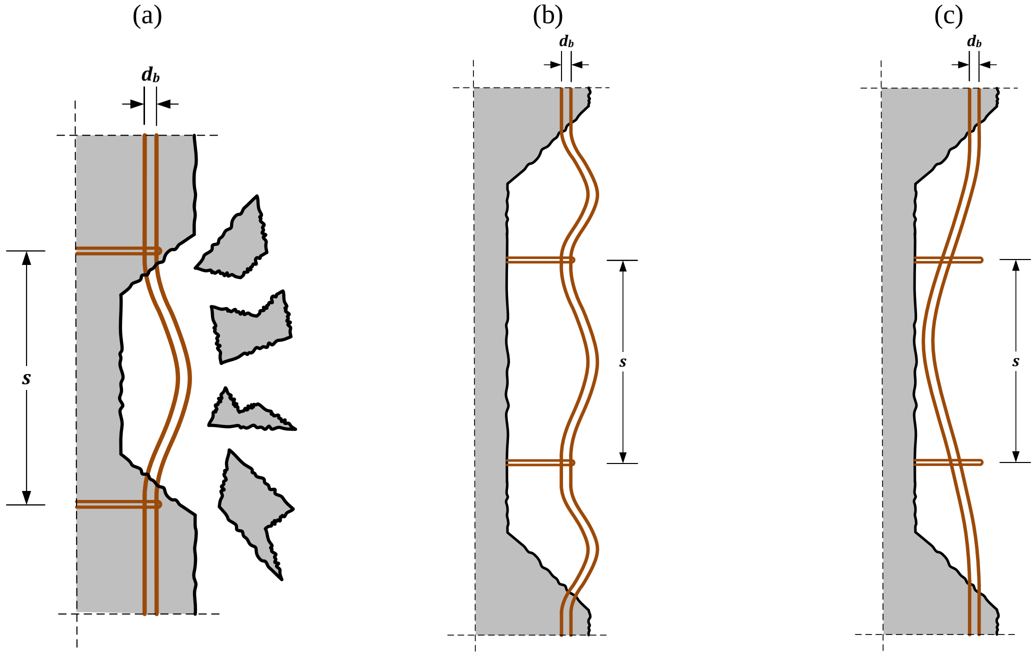


Figure 8 Local buckling of longitudinal reinforcement bar in column
(a) At the time of loss of column bearing capacity (overload, earthquake)
(b) Buckling model of longitudinal reinforcement between fixed points (stirrups)
(c) Assumed buckling model on the damaged part of the column while load with N_{Rd}

Researchers generally assume that the local buckling of longitudinal reinforcement bar will occur between two adjacent stirrups, thereby considering the bar as a column between two stiffened joints (Figure 8b).

However, Scribner and Wight [28] noticed that the longitudinal bars can buckle over the length of one stirrup interval, taking into account the predetermined damage of our column. It is evident that the main bar buckling under the limiting force N_{Rd} will look like the one in Figure 8c (with lesser deformation of the stirrups because of their bond with the main armature via wire).

5. CONCLUSION

Today's research on RC columns made of normal strength concrete (up to C 50/60) are primarily focused on the study of stress-strain relationship of the completed (new) element/column.

There is a large unexplored area of visibly damaged RC columns which take a large share in the exploitation of buildings built in the last century that are still widely used. It is necessary to answer the question of their bearing capacity, lifespan and vulnerability of the entire construction, because that part still remains insufficiently explored.

Also, the theories of local buckling of longitudinal reinforcement bar widely use assumption of uniform buckling between the stirrups on the principle of column buckling scheme between two fixed joints. This area requires further study and comparison with experimental results.

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