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ANALYSIS OF CONCRETE TAKEN FROM A LOADED COLUMN BY DETERMINING THE MODULUS OF ELASTICITY

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Abstract. Sustainability places an emphasis on preserving and using existing structures, particularly those that are historically or artistically valuable. The preservation of buildings is closely related to a good assessment of their condition. When making a diagnosis, it is suitable to use non-destructive methods to the greatest extent possible. However, these must also be complemented by core samples, which can be used to determine not only the compressive strength but also other important properties. The paper focuses on the evaluation of a reinforced concrete column that was gradually loaded until failure occurred. During loading, the quality of the concrete throughout the column was monitored using the ultrasonic pulse velocity method and, after loading was finished, the cores were taken from the column. The specimens, obtained from the core samples, were then carefully analysed using both non-destructive and destructive tests. The conclusion describes a possible approach to the assessment of concrete using a core examination.

Keywords: Concrete, column, load, ultrasonic pulse velocity.

1. Introduction

In September 2015, on the grounds of the General Assembly of the United Nations, the World Community approved the common goals of sustainable development, which should be achieved by 2030. It is a long-term program that should be implemented in all areas of human activity and that establishes 17 sustainable development goals. Incorporating sustainability criteria in the design and assessment of structures is necessary, and that is why it became the focus of attention of the research agenda in the last decade [1–3].

Requirements for the quality and durability of building materials keep changing – what is currently regarded as totally unsatisfactory may have been very common several decades ago. Assessment of existing structures is quite problematic in itself, especially in the case of historically or artistically valuable buildings. Assessment of structures related to their expansion, superstructure or simple repair is, from the perspective of sustainability, extremely demanding. To properly propose the procedure for a repair or superstructure of an existing structure, high-quality diagnostic research must be performed, including, among other things, the determination of the properties of the materials used [4]. In reinforced concrete structures, core testing is generally accepted as a reference method for determining the mechanical properties of concrete [5]. With regard to the sustainable development principles and protection of historic buildings, an increased emphasis is placed on their preservation, which leads to more frequent use of non-destructive methods in diagnostics [6]. However, it is not always easy or even possible to determine exactly the most critical parts of a structure without its disruption. Although the ultrasonic pulse velocity method, for example, enables the identification of internal defects, the determination of an even distribution of concrete in the structure or the determination of its compressive strength or modulus of elasticity, at least a minimum number of core samples is necessary [5].

If the purpose of concrete structure diagnostics is to learn as much as possible about concrete, only determining compressive strength using specimens obtained by core samples appears to be insufficient. The samples should be examined in more detail. What appears very suitable for this purpose are non-destructive methods such as the ultrasonic pulse velocity method or the resonance method [7]. These methods are commonly used to evaluate the degree of concrete degradation, for example, when testing the resistance to freezing and thawing, see [8], as they can be used to assess the extent of damage to the internal structure of concrete over time. In addition to compressive strength, the static modulus of elasticity can also be determined on the samples, since even partial damage to the concrete during its lifetime will affect its deformations under load.

2. The experiment

The concrete used for the column was designed so as to match as much as possible the concrete used in the middle of the 20th century in central Europe. The quality of concrete at that time corresponded to the knowledge and possibilities available in the production of cement, the design and the production of concrete. The difference between the construction of concrete structures at that time and today is primarily

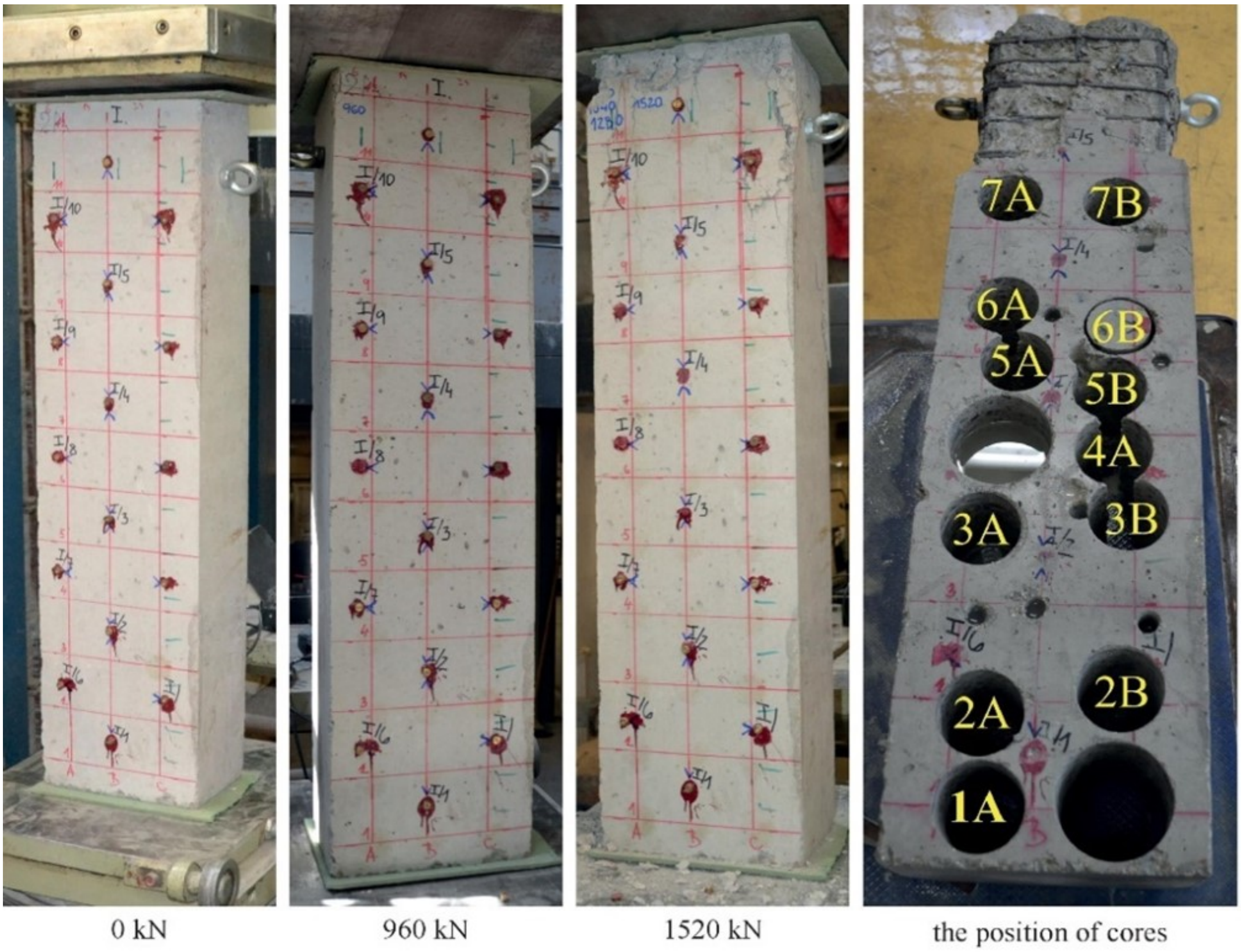

Figure 1. Concrete column under load of various degrees: at 960 kN, the first cracks began to form in the corners of the upper part of the column; at 1 520 kN damage to the upper third of the column is clearly visible (on the left and in the middle) and after cores were taken (on the right).

in the requirements for the concrete strength class based on the aggressiveness of the environment, the reinforcement coverage, and the effectiveness of the plasticizingadmixture used. Today, the requirements are much stricter and the plasticizing admixure more effective.

3. The material and the specimens

The column tested was made from the C16/20 strength class concrete with a minimal amount of plasticizing admixture and with coarse mined aggregate of a maximum size distributionof 16/32 mm. The column had a rectangular cross-section of 200 × 300 mm and a height of 1.2 m. The corners were reinforced with 4 steel rods B500B with a diameter of 16 mm. Stirrups with a diameter of 6 mm were located in an axial distance of approximately 115 mm and, at both ends of the column, the 3 stirrups at the edge were placed closer together (axial distance of 55 mm). The reinforcement coverage was 25 mm. More details on the column design and its reinforcement can be found in [9].

After loading, which is described in the next part of the paper, cores were taken from the column. For the experiment, 12 core samples with the nominal diameter of 75 mm were used; see Figure 1. From these cores, 12 specimens were prepared with a diameter of 75 mm and a length of 150 mm on which the quality of the concrete was analysed (or the extent of damage to its internal structure) using both non-destructive and destructive testing.

4. The testing procedure

The reinforced concrete column test was based on cyclic compressive loading with gradually increasing stress until the load capacity limit was reached. The column was placed in the test press so that the load acted centrally (Figure 2). The load step was set to approximately 1/12 of the assumed load capacity, so the column was loaded in steps of 80 kN. With each increase in the load, the ultrasonic pulse velocity (UPV) and deformations were measured over the entire area of the column. After each third increase in load, the column was unloaded to the basic force of 80 kN, which corresponds to a compressive stress of 1.33 N mm^{-2}.

The first visually detected concrete failure occurred

FIGURE 2. Concrete column under load placed in the test press.

at a force of 960 kN, that is, at a stress of 16 $N\,mm^{-2}$, specifically at the top of the column – the first cracks appeared in the corners. The last force achieved was 1 520 kN (compressive stress of 25.3 $N\,mm^{-2}$) when the concrete in the upper quarter of the column showed substantial damage, see Figure 1. The results of continuous measurement by the ultrasonic pulse velocity method discovered the failure of the concrete sooner than the first cracks appeared, see Figure 3. Before loading was started, it was found, using the UPV method, that in the upper part of the column the quality of the concrete is lower (UPV locally lower than 3 500 $m\,s^{-1}$) than in the lower part of the column (UPV locally higher than 4 000 $m\,s^{-1}$). Therefore, the resulting damage to the upper part of the column was not surprising. In contrast, the NDT results were confirmed by testing.

After loading was finished, cores were taken and specimens were prepared on which an analysis of the concrete behaviour was performed depending on its location in the column. First, the dynamic modulus of elasticity were determined using the UPV and resonance methods, which is partly described in [10]. UPV was determined on each specimen three times along its longitudinal axis using the Pundit PL-200 instrument according to the EN 12504-4 standard [11], based on which the dynamic modulus of elasticity E_{cu} was calculated according to the ČSN 73 1371 standard [12]. In addition, the natural frequency of longitudinal vibration of the specimens was measured using the Handyscope HS4 oscilloscope, based on which the dynamic modulus of elasticity E_{crL} was measured according to the ASTM C215-19 standard [13]. The static modulus of elasticity E_c was then determined on the specimensusing the DELTA 6-300 press according to the ISO 1920-10 standard [14], as well as the compressive strength fc. When E_c was tested, a continuous record of the acting force and the deformations was made using a data recorded.

5. The results and their discussion

The values of compressive strength and modulus of elasticity determined in the specimens are shown in Table 1. The data measured during the E_c test were used to calculate the modulus of elasticity of the first loading cycle, which can be considered the initial secant modulus of elasticity $E_{c,0}$, as defined in the EN 12390-13 standard [15].

Specimen	E_{cu} [GPa]	E_{crL} [GPa]	$E_{c,0}$ [GPa]	E_c [GPa]	fc [$N\,mm^{-2}$]
1A	33.64	31.93	25.96	27.54	47.57
2A	36.34	32.33	20.92	22.81	47.07
2B	36.23	35.29	28.12	28.54	48.82
3A	30.99	24.67	18.74	20.68	35.18
3B	33.71	29.86	21.16	24.57	33.82
4A	34.55	28.84	21.90	22.51	35.21
5A	34.23	28.75	18.91	21.07	37.66
5B	32.94	27.68	18.31	21.12	35.75
6A	29.93	26.09	21.15	23.76	32.70
6B	31.38	23.93	20.72	21.39	32.46
7A	26.53	20.16	16.05	18.07	26.70
7B	26.83	21.96	13.99	15.91	27.98

TABLE 1. Results obtained for each specimen.

It is quite interesting that for the specimens taken from the column subjected to a considerable load, there is almost no dependence on the dynamic and static modulus of elasticity; see Figure 4. For all the dependences described below, the simplest regression model, a line, was chosen – the graphs show that more complex models would not achieve significantly better results and, therefore, would not be justifiable. The dynamic modulus of elasticity determined by the UPV method is almost completely independent of the static modulus of elasticity – the coefficient of determination R^2 only reaches 0.536. For the dynamic modulus of elasticity determined by the resonance method, the dependence is greater ($R^2 = 0.740$) but it is definitely not statistically significant. It is even more interesting that the dynamic modulus of elasticity show a greater dependence on the compressive strength; see Figure 5. For the dynamic modulus of elasticity, the coefficient of determination R^2 is equal to 0.838, which indicates a statistically significant dependence, although it has been proven that, with concrete, there is no direct dependence of its modulus of elasticity and compressive strength; see, for example [14, 15].

A significant dependence of $E_{c,0}$ and E_c is quite common, since they are two outputs from one test. Despite that, the difference in the ratio of $E_{c,0}$ to E_c in the specimens tested is not negligible – it ranges from 0.99 (specimen 2B) up to 0.88 (7B), 0.87 (5B) and 0.86 (3B). The greater the difference between $E_{c,0}$ and E_c, the greater the permanent deformations after the first cycle. This can mean micro cracks and other

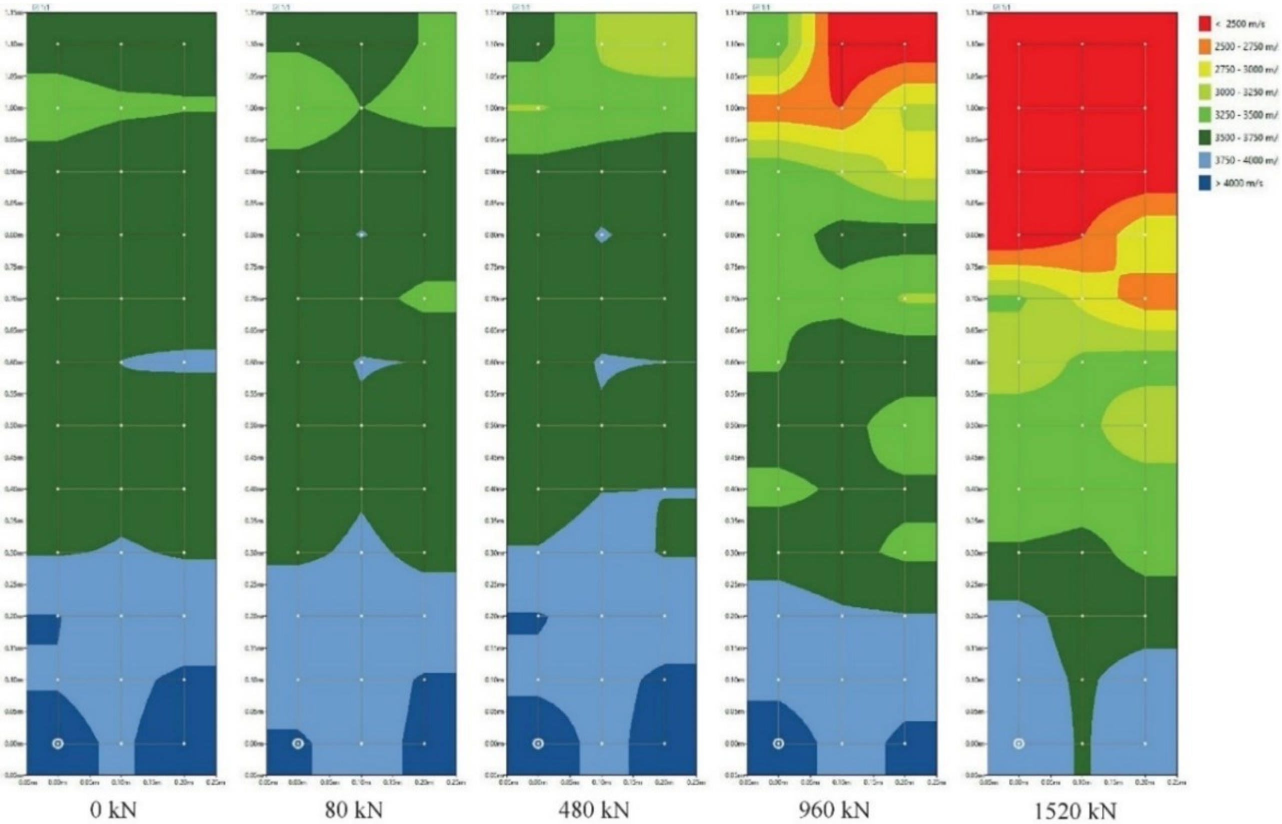

FIGURE 3. The distribution of UPV across the column area , which was determined under a load of various degrees.

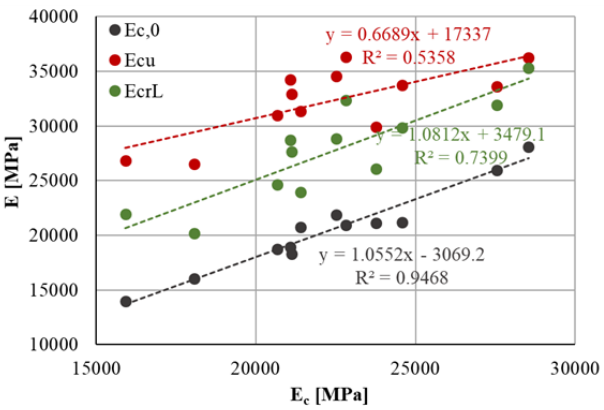

FIGURE 4. Dependence of the modulus of elasticity $E_{c,0}$, E_{cu}, and E_{crL} on the static modulus of elasticity.

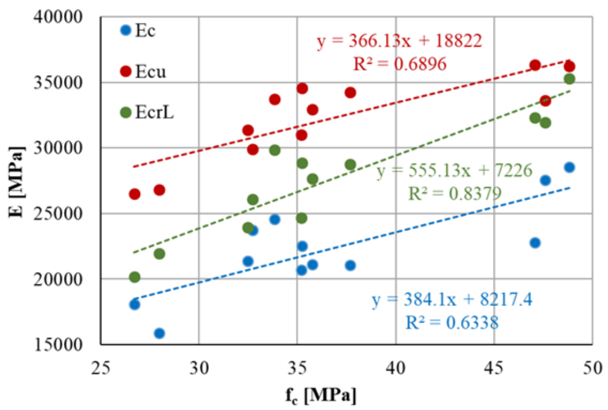

FIGURE 5. Dependence of the modulus of elasticity E_c, E_{cu}, and E_{crL} on the compressive strength.

microdefects in the internal structure of the concrete in the specimen. When testing the static modulus of elasticity, no flexible recovery of the deformations of the specimen takes place after its unloading to the basic level of stress (beginning of the second cycle). Therefore, in the following cycles, a smaller difference in the deformations is measured, leading to a higher value of E_c. In Figure 6, more considerable permanent deformations are apparent in specimen 5B, which leads to a lower $E_{c,0}$ to E_c ratio and to the conclusion that specimen 5B is more damaged than specimen 2B.

Figures 1 and 3 show how the damage to the concrete column occurred. Approximately the top quarter of the column was so damaged that it was not possible to take solid core samples from this area. The extent of damage to the concrete decreased with the column height and approximately the lower quarter was damaged the least, see Figure 3. This is also confirmed by the results obtained for the specimens, when the values determined are related to the location from which the cores were taken with regard to the column height. The values of the properties of the specimens designated by the same figure (i.e., taken from the column at the same height) are represented by the mean value. The data are again fitted with a line re-

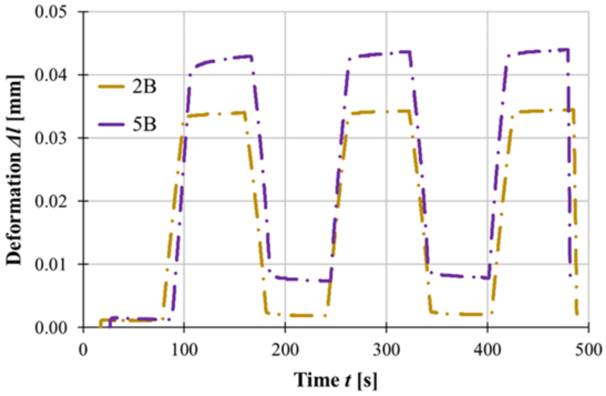

Figure 6. Development of the deformations of specimens 2B and 5B during the static modulus of elasticity test.

gression model. The most significant dependence was found for the static modulus of elasticity ($R^2 = 0.89$), then for the compressive strength ($R^2 = 0.87$) and the dynamic modulus of elasticity determined by the resonance method ($R^2 = 0.85$). On the contrary, almost no dependence related to the location of the specimens in the column was found for the dynamic modulus of elasticity determined by the UPV method.

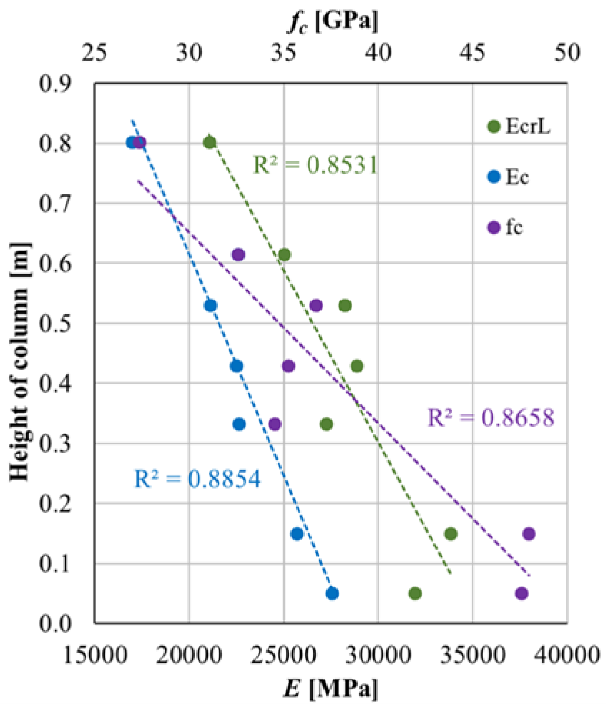

Figure 7. Dependence of the modulus of elasticity and the compressive strength on the height of the location where the specimens were taken from the column.

6. Conclusion

Based on the measurements performed, the following can be stated:

- The ultrasonic pulse velocity method can be used to reliably detect a failure of concrete in a column under load. The measurement results obtained by the UPV method before loading reliably predicted the area where the greatest damage would occur.
- The resonance method produces a very good response to damage to the internal structure of the core concrete, which appears to be more suitable than the UPV method when measuring the cores.
- The ratio of the initial secant modulus of elasticity to the static modulus of elasticity is connected with the failure of the concrete of the specimen. The more damage caused by microdefects in concrete, the greater the permanent deformations detected and the lower the ratio of $E_{c,0}$ to E_c.
- To make a detailed assessment of the quality of concrete, it is necessary to carefully analyse the behaviour of the core specimens. Besides the values of permanent deformations, it is useful to analyse the ultrasonic pulse signals and the signal detected by the resonance method.

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