Damage Assessment of Concrete Column using Combination of Nondestructive Methods

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Abstract

During construction of viaduct "Stara Susica" on the highway Zagreb – Rijeka in Croatia due to unpredicted mistakes in the execution works sudden fall of prestressed prefabricated beam girder (30 meters long and around 100 tons weight) had happened. During the fall the girder hit the column in its second third of height and caused significant damage of reinforced concrete column. Preliminary visual inspection implied only local damage of surface concrete of the column cross-section, without the indication of deeper structural damage. The combination of nondestructive techniques (ultrasonic pulse velocity and impact echo method) was used for the assessment of column structural damage, which had shown significantly greater structural damage of concrete, with deeper cracks detected within the concrete column than firstly visible from the surface. The combination of nondestructive methods gave a better image of structural damage, considering the size and depth of damage, which was the base for the design project of the column repair (choice of repair methods, technology and materials). In this case study nondestructive evaluation improved both the efficiency and accuracy of column inspection and justified its application in the structural damage assessment.

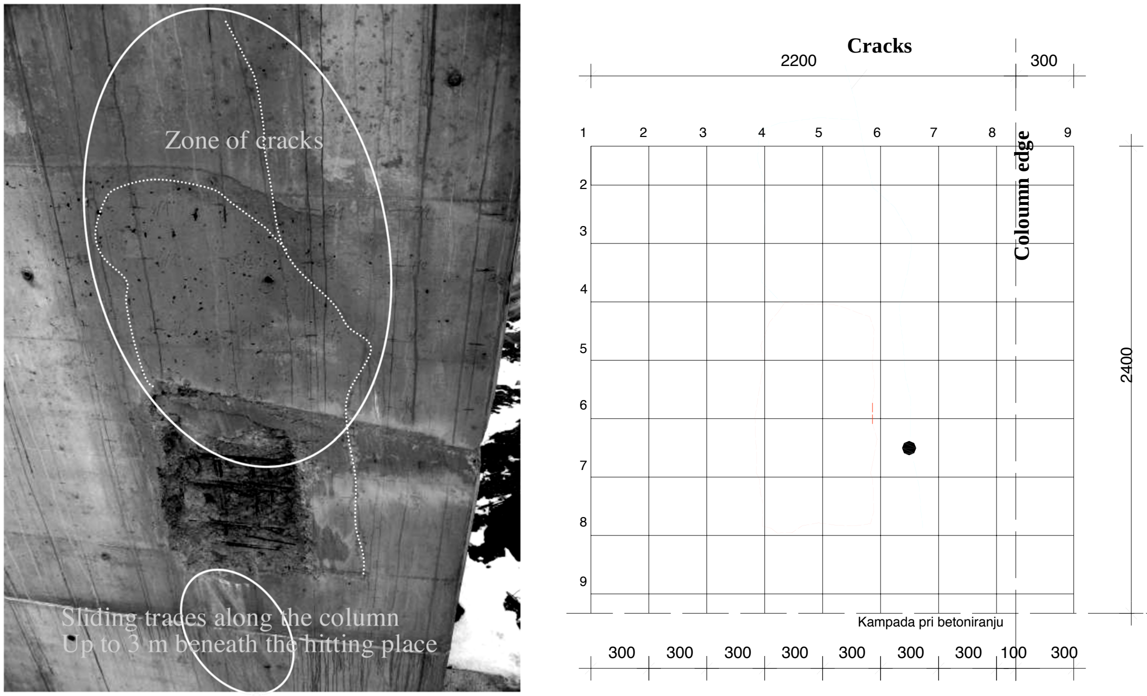
INTRODUCTION

Paper describes condition assessment with the application of NDT methods during nondestructive damage investigation on the 18 m high reinforced concrete column on highway Zagreb - Rijeka in Croatia (Figure 1). Column was damaged by sudden fall of prestressed prefabricated beam girder of about 30 meters long and 100 tons weight, caused by carelessness during construction works. During the fall the girder hit the column which caused significant damage of column at the upper third of height.

Figure 1: (a) Failure on viaduct Stara Susica on Zagreb – Rijeka highway (b) Damaged column.

VISUAL INSPECTION AND PLANNED FURTHER INVESTIGATIONS

First insight into damaged column state was obtained by visual inspection. Visual inspection gave local damage on surface concrete, of the about 10 cm depth and of (120 x 80) cm^2 area. Two cracks of 0,1 mm width, and of about 1 m length, were visible above damage. Also, sliding traces along the column were detectable and visible up to 3 m beneath the place of impact.



(a) (b)

Figure 2: Visible column damages (a) on photograph (b) indicated on measuring mesh.

It was concluded that visual inspection isn't sufficient for complete damaged area detection and it was decided to investigate wider area around visible damages by nondestructive methods. For this purpose, a measuring mesh covering area of about (240 x 200 cm) with line separation of 30 cm is drawn. Figure 2(b) shows a mesh compared with visually indicated damages. It was planned to employ two nondestructive test methods, an impact echo method and time of ultrasonic pulse propagation method.

MEASUREMENTS BY IMPACT ECHO METHOD

Impact echo equipment consists of mechanical impactor, accelerometer for stress wave detection, A/D converter and of tablet PC with software for data acquisition and analysis.
Stress wave generated by mechanical impactor of defined mass; propagate through concrete by certain velocity, which depends on modulus of elasticity of concrete. Stress wave is reflected from boundary of structural element (Figure 3 (a)) or from flaw (Figure 3 (b)) [1].

Time Δt required for elastic wave propagation through concrete to boundary plane (or flaw) and back to detector is given by equation 1.

$$\Delta t = \frac{2D}{v_p}, \tag{1}$$

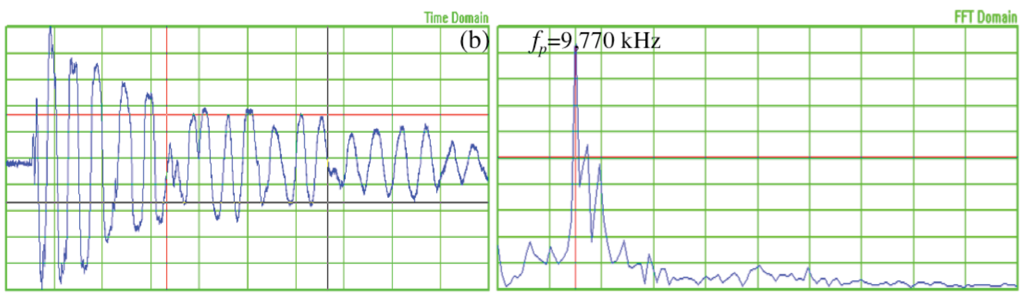
where, D is thickness of structural element i.e. flaw depth and v_p is velocity of elastic wave propagation.

Figure 3: (a) P-wave reflection from element boundary (b) P-wave reflection from flaw.

To simplify data analysis, data acquisition and analysis software converts signal consisted of *N* measurement data recorded in time domain into frequency domain by Fast Fourier transformation (*FFT*) algorithm described with relation 2.

$$FFT\ I(f) = \sum_{t=0}^{N-1} I(t) e^{ift/N} \tag{2}$$

After *FFT* application, measured data shows peaks on certain frequencies (Figure 4 (b)), which simplifies data interpretation.



(a) **(b)**

Figure 4: (a) Measured data in time domain, (b) Measured data in frequency domain after *FFT*.

As, frequency and time is connected by:

$$t_p = \frac{1}{f_p}, \tag{3}$$

it follows equation for depth of flaw (or structural element thickness) calculation from FFT data.

$$D = \frac{V}{2 f_p}. \tag{4}$$

Impact echo results and analysis

Ultrasonic pulse velocity, necessary for depth of flaws detection was determined on drilled no damaged concrete cylinder shown in Figure 5 by impact echo method and time of flight method by “PUNDIT” device.

Figure 5: A cylinder drilled from no damaged position.

P-wave speed, v_p is calculated according to relation 1 from impact-echo frequency f_p and measured cylinder height D. P-wave velocity from time of flight measured by Pundit device is calculated applying Equation 5. Both methods gave average ultrasonic speed of about 5300 m/s.

Measurement results obtained by Impact – echo are converted into frequency domain by FFT algorithm. On frequency – intensity graphs different patterns of measured signal was recognized, which can be classified according to [2, 3, 4]. Non-damaged concrete is characterized with one sharp peak at frequency corresponding to element thickness. Such example is shown in Figure 6, for measurement point (3, 9) from mesh (Figure 2(b)), where peak on frequency of 9,281 kHz corresponds to thickness of structural element of 26 cm. No other peaks with similar or greater intensity exist, so it can be concluded that concrete at a point (3, 9) is no damaged. Similar patterns appeared at other points characterizing undamaged concrete.

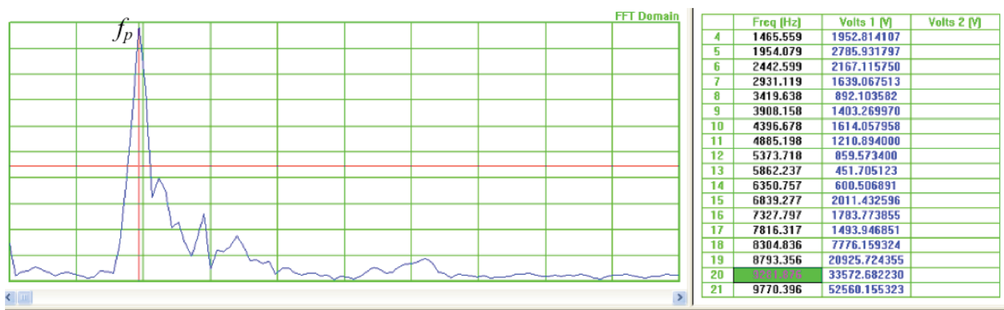


Figure 6: Example of waveform for no damaged concrete (point (3, 9) on a measurement mesh).

Other observed types of waveforms, with characteristic patterns shown bellow describe damaged concrete. Although classification of damaged concrete is possible [2, 3, 4], for the scope of this particular investigation it wasn't necessary, because the purpose of these investigations works was to identify appearance of any damages caused by incident on the structural element, which before fault was in perfect condition.

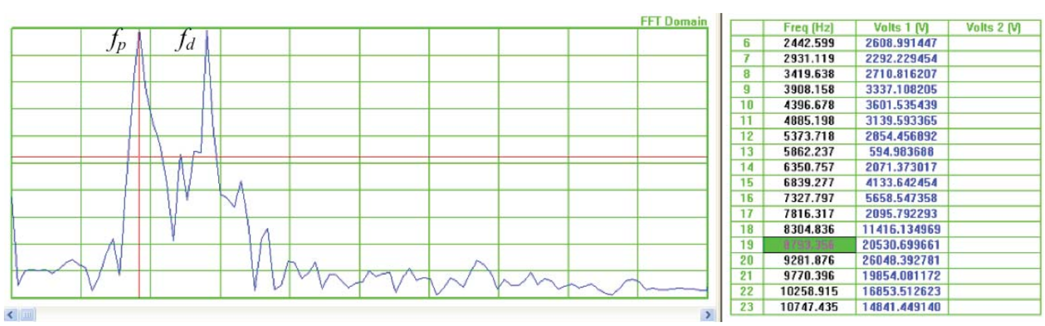


Figure 7: Example of waveform for damaged concrete with one significant flaw (point (1,1)).

Figure 7 shows example of waveform for damaged concrete with one significant flaw, positioned on the depth of 18 cm, calculated from frequency of second maxima applying Equation 1. First maxima correspond to thickness of structural element (27 cm). Thickness is detectable which means that flaw isn't large and acoustic energy can propagate beside flaw. Second possibility is that wave propagates directly from the impactor to the bottom plane of element, but flaw is situated apart [2]. These type of measurements was characterized as damaged concrete.

Next example, shown in Figure 8 represents situation of rather poor condition of investigated concrete. Thickness is hardly detectable, because small portion of wave is reflected from bottom boundary, and several cracks are detectable. This measurement is performed on the coordinate (6, 3) near the crack visible from the surface.

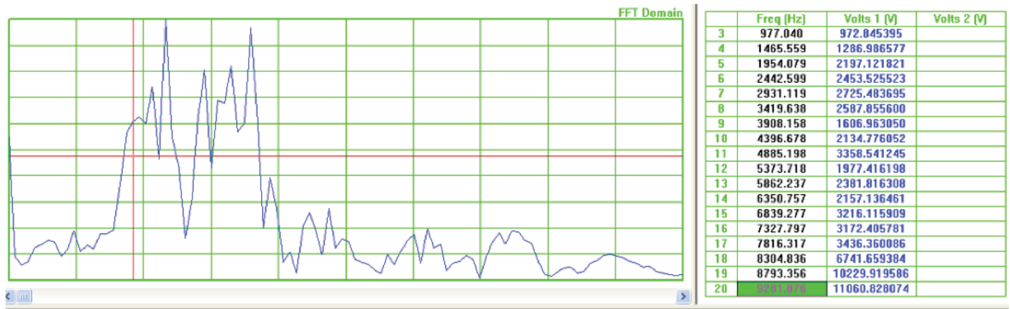


Figure 8: Example of waveform for considerable damaged concrete with several significant flaws (point (6, 3) on a measuring mesh).

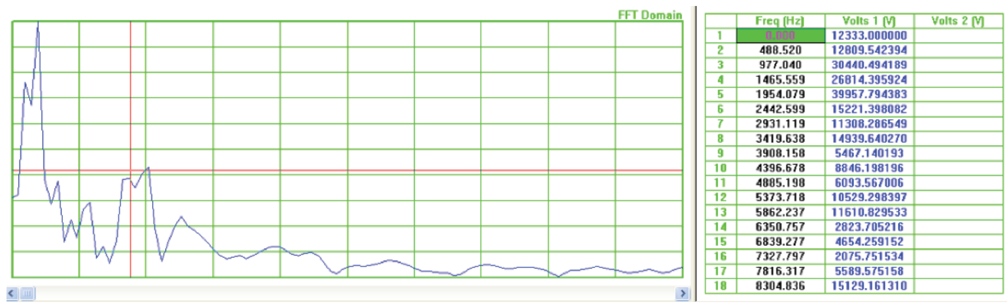


Figure 9: Example of waveform for concrete delaminated near the surface (point (4, 3) on a mesh).

For the example in Figure 9 frequencies are lower than the frequency which determines element thickness, so calculation of depth according to equation 1 gives values greater than structural element thickness, hence cannot be applied. Sources of low frequency maximum are flexural vibrations of delaminated area. Conclusion is that an area of unbounded layers from other concrete exists, which is at small depth allowing low-frequency vibrations.

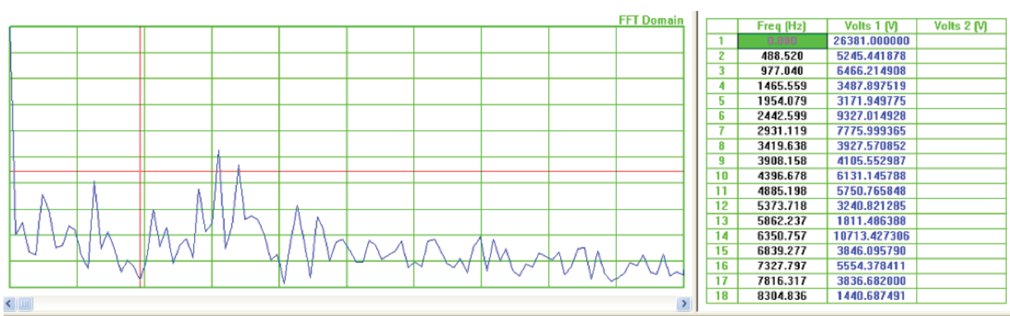


Figure 10: Example of waveform for concrete delaminated near the surface (point (6, 6) on a mesh).

Measurement giving waveform shown in Figure 10 is performed near the visible crack and drilled core.

(a) (b)

Figure 11: (a) Drilled hole near the position (6, 6) and (b) corresponding core.

Drilled core (Figure 11) shows seriously damaged concrete, which is affirmed by signal pattern (Figure 10). Thickness of element isn't detectable because all acoustic energy is reflected from many cracks and fragments. Also, Figure 10 shows frequencies smaller than frequency which represents thickness of structural element, which leads to flexural oscillations of larger rebounded areas situated near the concrete surface.

Impact-echo results for overall investigated area are represented in Figure 12. Damaged places are marked red and undamaged places green. From Figure 12 it can be seen that damaged area spreads outside of visible damage. It is estimated that on the right side of column damages spreads up to 40 cm from column edge.

Damages are spreading above the measured area on the left side and below, where concrete girder slipped during falling. Figure 12 also shows visible cracks indicated by blue dotted line, visible deterioration indicated by red dotted line, and position of drilled core indicated with black dot.

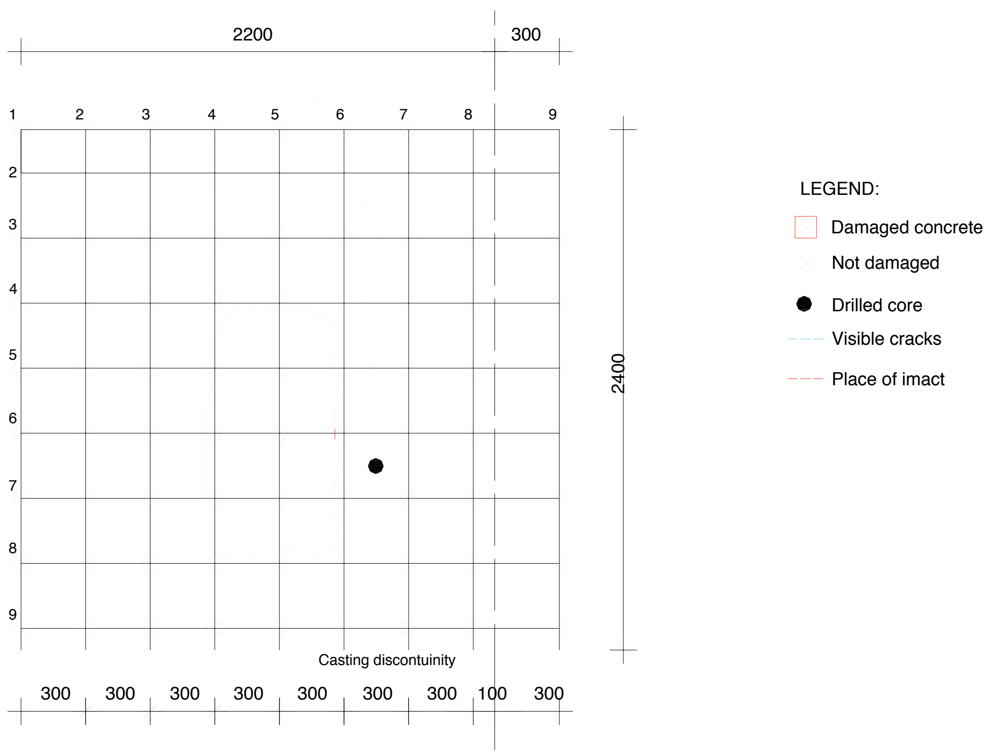


Figure 12: Impact echo test results for investigated surface.

ULTRASONIC PULSE TRANSIT TIME METHOD

Ultrasonic pulse transit time method is based on the measurement of time, required for ultrasonic pulse propagation through investigated concrete element, from which pulse propagation velocity can be calculated according to:

$$v_p = \frac{D}{t}, \tag{5}$$

Where, t is time required for pulse propagation and D is distance between transducers.

Velocity v_p is correlated with dynamic modulus of elasticity of concrete and with degree of concrete deterioration [5].

Two test configurations are used, non-direct configuration which uses transmitter and receiver situated on same plane (Figure 13 (a)), and semi-direct configuration where transmitter and receiver are placed on two planes at the angle of 90° (Figure 13 (b)) [6]. These test configurations are suitable for crack depth determination. Ultrasonic pulse arising at the crack cannot bridge over, so it propagates on path which requires minimal time to arrive to the detector. Result is time of flight increasing, which makes possible determination of the crack depth. Ultrasonic wave propagation paths, which require minimal time, are indicated with red lines (Figure 13).

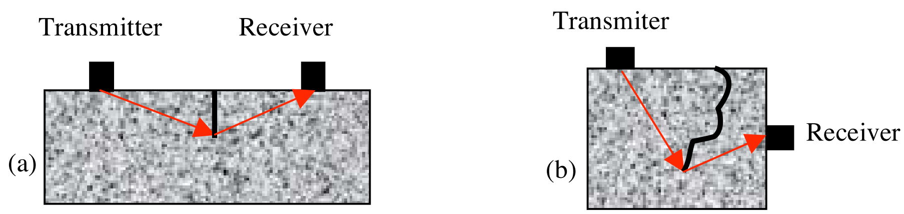


Figure 13: Crack depth measurement principle (a)non-direct method, (b) semi-direct method.

In the case of seriously damaged concrete, with many cracks, result is large decrease of ultrasonic pulse propagation time.

Ultrasonic pulse method results and analysis

Ultrasonic pulse time of flight method is chosen to confirm results obtained from impact – echo method and to detect depth of visible cracks. On the column surface indirect method is used. Some measurements are made by positioning transmitter and receiver to bridge visible crack, for which crack depths were calculated and are shown in Figure 14.

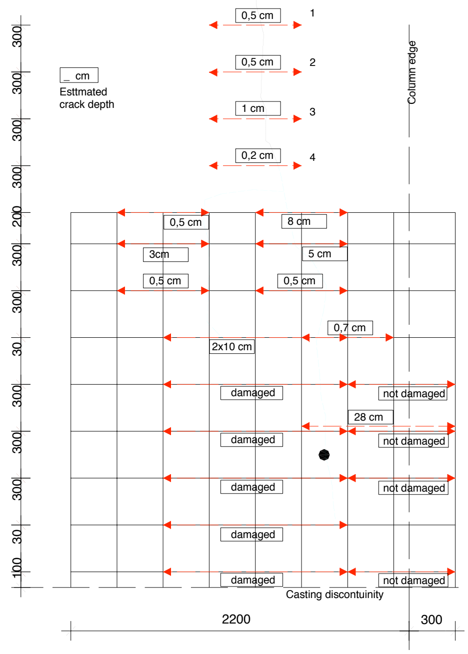


Figure 14: Results of ultrasonic pulse transit time measurements.

Near the drilled cylinder, a crack which spreads through overall column wall depth is detected, while in the upper part of measurement mesh depth of crack is smaller, from 0,5 cm to 8 cm. Measurements were performed also along the whole crack, which spreads about 1 m upper from the mesh. For these positions small crack depth was indicated (0,2 to 1 cm). Another series of measurements was performed by semi-direct method around the right column edge. Results of these measurements indicated non-damaged concrete. Measurements were performed also across the visible damaged area and these results indicated high decrease of ultrasonic pulse velocity (from 5300 m/s for sound concrete to 2000 m/s) which is an indication of several damages under the visible damaged area.

CONCLUSION

For investigated reinforced concrete structural element damaged by strong impact, it appears that visual inspection cannot give satisfactory data required for estimation of complete damaged area. Therefore, it was necessary to employ nondestructive test methods. From data analysis it is evident that both practiced nondestructive test methods (impact echo and pulse transit time) are quite useful for such type of damages characterization. Both methods lead to similar conclusions about damaged area and state of structural element and supplement each other.

Cores drilled on two positions, for which nondestructive methods gave indication of seriously damaged concrete and of no damaged concrete, confirm results obtained by nondestructive test methods.

On the basis of the performed investigation works it was estimated damaged area spreads on the maximal possible width of about 2,5 m and height of about 5 m, which is 20 % of total column cross section (Figure (5(a)).

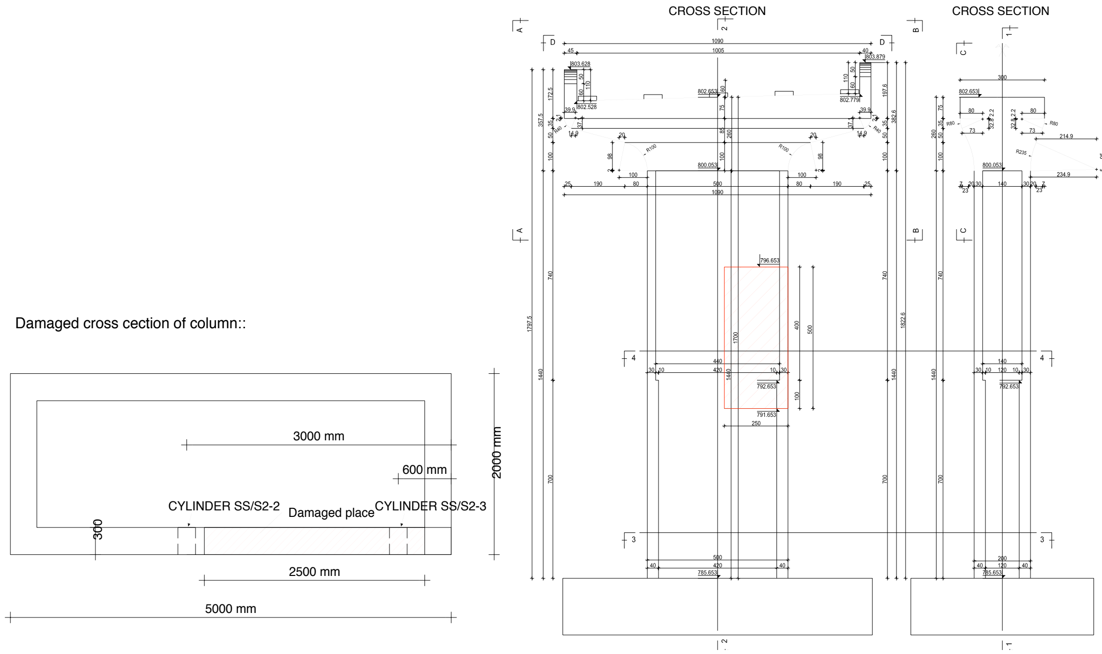


Figure 15: (a) Damaged cross section of column (b) Damaged area (red indicated).

Figure 15(b) shows estimated damaged area in respect to whole column.

As result of investigations proposal for repair project was given, including statically analysis of column load bearing capacity caused by cross section decrease during damaged concrete removal, removal of damaged concrete by hydro demolition; loosen formwork inside the column body montage, reinforcement repair, exterior formwork montage, implementation of new concrete and finally testing of quality of performed works.

REFERENCES

1. Carino, N.J., “The impact-echo method: an overview,” *Proceedings of the 2001 Structures Congress & Exposition*, May 21-23, 2001, Washington, D.C., American Society of Civil Engineers, Reston, VA, Peter C. Chang, Editor, 18 pp. 2001.
2. Shokouhi P., N. Gucunski, and A. Maher, “Applicability and Limitations of Impact Echo in Bridge Deck Condition Monitoring”, *12th European Meeting of Environmental and Engineering Geophysics - Near Surface*, September 4, 2006, Helsinki, Finland. 2006.
3. Gucunski N., Maher A. And Vitillo N, “Bridge Deck Evaluation Using Portable Seismic Pavement Analyzer (PSPA) ” *Final Report FHWA NJ 2000-05 CAIT 26*. 2000.
4. Valenzuela, M., M. Sansalone, C. Krumhans, and W.B. Streett, “Use of sound for the interpretation of Impact-Echo Signals”, *Proceedings of 4th Conference on Auditory Display*, pp. 47-56. Palo Alto, CA., Nov. 1997.
5. Sekulic D., D. Bjegovic, D. Mikulic, Nondestructive Testing Methods for Concrete Structures Assessment, *MATEST 2001*, Cavtat – Dubrovnik. September 23-25 2001.
6. *Guidebook on nondestructive testing of concrete structures*, Training course series No. 17, (IAEA–TCS–17) International atomic energy agency, Vienna. 2002.