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ASSESSMENT OF STRUCTURAL CONCRETE AFTER CONTACT DETONATION ACTION

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Abstract:

High dynamic actions like high velocity impacts or shock waves due to detonations lead to damages in reinforced concrete structures. Both under civilian aspects as well as with military regards high dynamic actions are an important topic of security of infrastructure worldwide.

The damages caused by contact detonations at reinforced concrete structures are characterized by a central target area, which is visually recognizable. But usually there is also an obvious invisible damage in the surrounding material caused by shock wave propagation through the concrete and displacement and vibration of reinforcement bars. To make a statement concerning the structural behavior of reinforced concrete structures damaged in such a manner and to predict their residual load bearing capacity in a further step, information on the damage is needed. To assess the size of the whole damaged zone consisting of visible and obvious invisible parts, non-destructive tests (NDT) have been carried out. Investigations showed good applicability with using the acoustical-based testing method Impact-Echo and the Radar system based on electro-magnetic waves.

This paper includes a short introduction of the NDT-methods used, describes experimental investigations with reinforced concrete slabs damaged by contact detonation and shows the possibilities and the range of application of methods to assess damages of reinforced concrete components caused by high dynamic loads.

1. MOTIVATION

High dynamic loads - for example a vehicle impact or blast and shock waves due to detonations - lead to damages in reinforced concrete structures. These damages are characterized by a central zone, which is visually recognizable and also an obvious invisible damage in the surrounding material caused by shock wave propagation through the concrete (surrounding zone, see figure 1). This damage in the surrounding zone is characterized by a deterioration of the concrete's microstructure as well as bond failure between reinforcement bars and concrete.

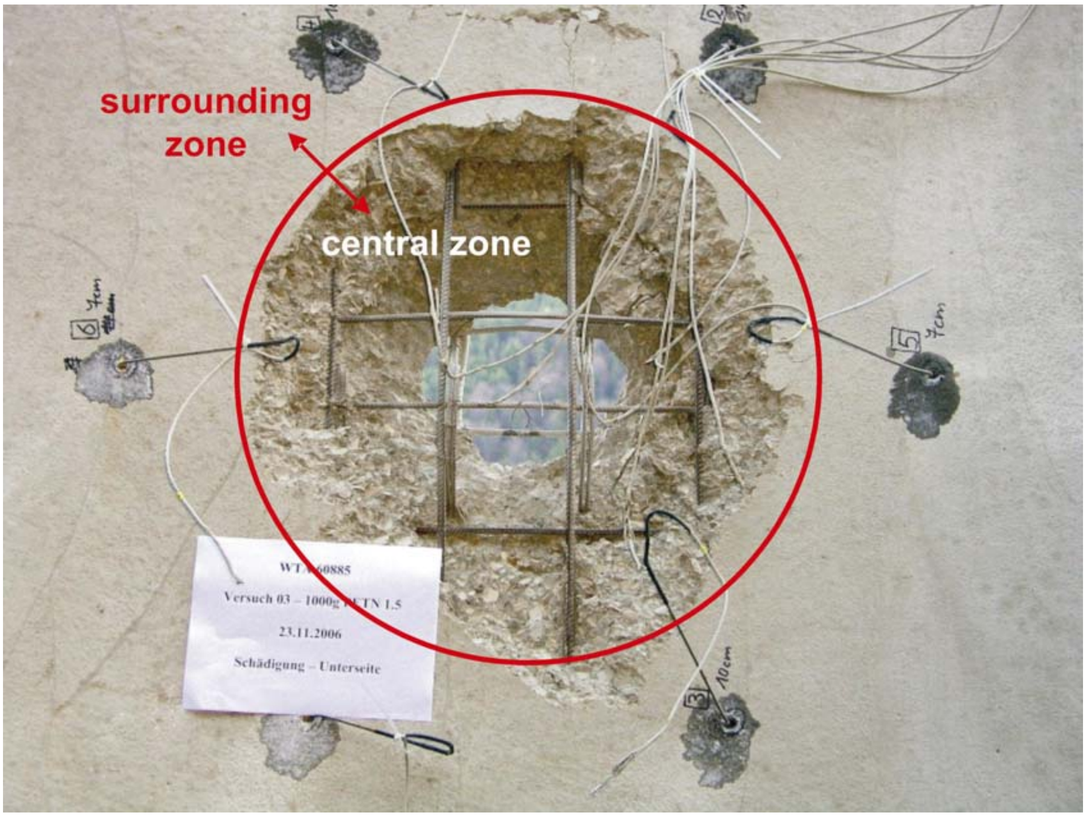

Figure 1: Zones of damage after contact detonation action

To make a statement concerning the structural behaviour of reinforced concrete structures damaged in such a manner and to predict their residual load bearing capacity in a further step, information on the damage's intensity and size is needed. One possibility to assess the size of the total damaged zone consisting of visible and obvious invisible parts is non-destructive testing (NDT). The use of the acoustical-based Impact-Echo-method (IE) and the Ground Penetrating Radar system (GPR) based on electro-magnetic waves seem to be appropriate for that particular problem.

2. ECHO-METHODS FOR DAMAGE DETECTION IN REINFORCED CONCRETE

2.1 Impact Echo Technique

Developed in the middle of the 1980ies by *Carino* and *Sansalone* [1] in the United States, the Impact-Echo method uses transient stress waves generated on the surface by an elastic impact. As the stress waves propagate through the tested material, they are reflected by internal interfaces (discontinuities in the material) and external boundaries of the structure (see figure 2).

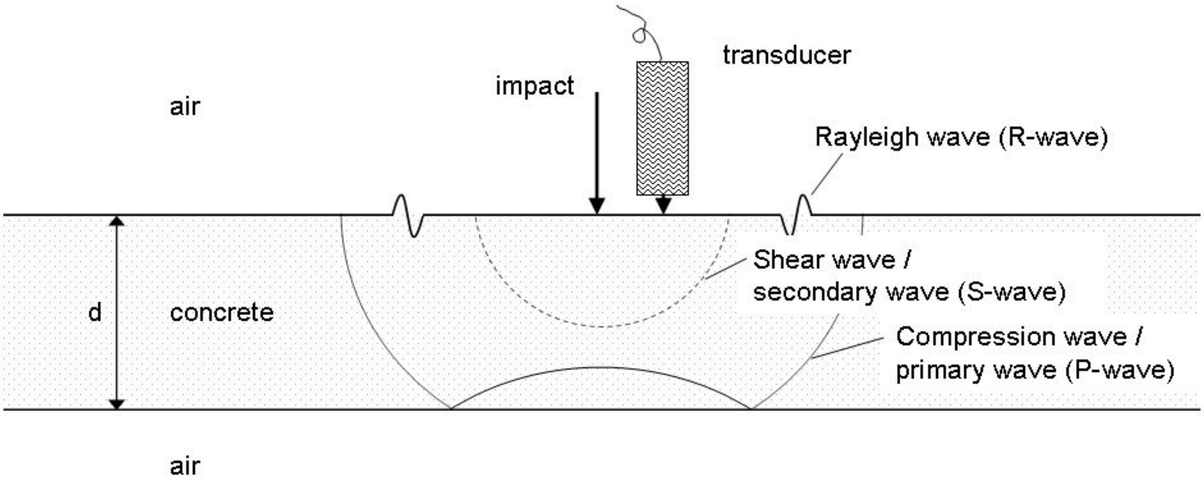

Figure 2: Impact-Echo Principle

Examples for such interfaces are delaminations, voids and cracks, as well as rising mains or large steel bars. In order to detect such interfaces, the emitted compression waves (p-waves) are recorded by a displacement or acceleration transducer which is placed near the impact point on the surface of the structure [2].

The depth of any internal flaws or external interfaces can be determined by analyzing the recorded signal and its characteristic frequency spectrum, which is obtained via a Fast Fourier Trans-formation (FFT) using the following basic equation:

$$d = \frac{C_p}{2 \cdot f_R} \qquad (1)$$

In equation (1) d is the depth of the interface or void, C_P is the compression wave velocity and f_R is the resonance frequency in the spectrum corresponding to the period T of the wave. Usually the resonance frequency is the dominant frequency in the spectrum. Together with the p-wave velocity of the particular material, the depth of the void can be evaluated using equation (1) [2].

The velocity of the compression wave (p-wave) of the tested structure must be well-known. In general three possibilities to determine the p-wave velocity can be mentioned:

1. Estimation of the p-wave velocity (a usual value for hardened concrete is 4000 m/s),
2. direct measurement of the p-wave velocity, when the thickness of the tested object is known (i.e. by using a carrot) and
3. calculation of the p-wave velocity using a known p-wave velocity C, which can be measured at the surface with the help of two transducers.

In general the p-wave speed in a 2-dimensional space is dependent of the material's young's modulus E, its density ρ and its Poisson's ratio ν according to equation (2).

$$C_P = \sqrt{\frac{E \cdot (1-\nu)}{\rho \cdot (1+\nu) \cdot (1-2\nu)}} \tag{2}$$

For assessing damages in structural concrete with IE a determination of damages has to be made. To detect damages like surface parallel delaminations, voids in tendon ducts or surface opening cracks, these flaws must have suitable size to enable reflection of the compression wave. In the past a lot of work concerning the use of IE for the assessment of these kinds of damages has been done. For example research work has been carried out relating to the detection of delaminations in concrete [3], investigations of voids in tendon ducts of prestressed structures [4], determination of cracks [5, 6] and bond quality between concrete and reinforcing steel bars [7].

If the concrete's microstructure is damaged, e.g. the appearance of cracks with very low crack widths, bond failure of the contact zone aggregate - hardened cement paste, or micro cracking in general, the compression waves are not completely reflected because of the minor dimensions of flaws. According to *Cheng* and *Sansalone* [5, 6] for full wave reflection the minimum crack width needed is 0.08 mm. Crack widths between 0.025 mm and 0.08 mm lead to partly refraction / partly reflection of p-wave. Lower crack widths than 0.025 mm induce full wave refraction.

Nevertheless IE can be used for assessing the distribution of damages in concrete's microstructure. The effect that has been observed with this kind of damage is a decrease of signal runtime and the equivalent p-wave velocity respectively. Providing that the thickness of the damaged structural component investigated is known, the p-wave velocity can be determined.

The range of regular p-wave velocity varies from 3500 m/s to 4500 m/s depending upon concrete composition, age and condition. The acceptable variation in C_P for a given batch of concrete was determined to be approximately 2 to 2.5 %. Therefore, p-wave velocity measurements across structures that vary by more than 100 m/s would indicate concrete deterioration. This has been observed by Tawhed and Gassman [8] for bridge decks loaded at service load level.

2.2 Ground-Penetrating-Radar

Ground Penetrating Radar (GPR) has primarily been developed for geophysical applications. In the last years GPR also has been used for the evaluation of reinforced concrete structures, and bridge decks in particular. This got possible by the use of antennas with a higher frequency range (400 MHz up to 2.5GHz). GPR is based on the propagation of electromagnetic waves (EM) and their reflections at interfaces (i.e. reinforcement steel / concrete or post-tensioning tendons / concrete) and flaws within the material investigated.

Usually for testing with one-side accessibility only the reflection measurement is used. Hereby the emitting and receiving antennas are installed at one level with a fixed distance. The combined antennas are pulled along one line to generate a linescan. A more detailed explanation of the principle and the physical background as well as a setup of the needed gear is exemplarily given in [9] and [10].

Unlike the Impact-Echo method the determining attributes for propagation of electromagnetic waves are the material's dielectric properties. For porous materials like concrete these properties are mainly dependent of concrete's relative humidity (moisture) and its permeability [11]. This fact can be used for an indirect detection of deterioration of concrete's microstructure. Zones of deteriorated concrete are characterized by lower density and higher porosity and consequently alternative moisture content and alternative relative permittivity.

3. EXPERIMENTAL INVESTIGATIONS

3.1 Test specimen

The experimental investigations have been carried out at reinforced concrete slabs (size 300 cm by 400 cm and 200 cm by 200 cm) and thicknesses of 20 and 30 cm. They consist of standard concrete C30/37 according to the German code DIN 1045 and are reinforced with two layers of orthogonal steel reinforcement. The slabs have been loaded either with a contact or with a near field detonation consisting of different amounts of explosives from 400 g PETN to 2750 g PETN. The slabs have already been used for a parametric study concerning the impact of the amount of explosives to the resulting crater volumes (see [14]). The loading of the slabs has been carried out by the Technical Center for Protective and Special Technology (WTD52) in Oberjettenberg, Germany.

The visible damage in the central zone consists of spalling at the front side (side of loading) and scabbing at the rear side of the loaded slab. Moreover some of the specimens show a perforated central zone. The behaviour of concrete at high strain rates has been investigated intensively in the past and is still a topic of recent international research. Experimental work and numerical studies have been carried out. An overview of the current state-of-research is exemplarily given by *Stempniewski et al.* in [12].

3.2 Impact-Echo: test setup and results

For the IE tests a commercial system with mechanical impact stimulation for measurements at discrete spots has been chosen. Before the measurement starts a chalk grid has to be applied on the surface of the specimen. At this it is important to locate the test spots not directly above the axis of reinforcement bars to get a signal which allows a reliable interpretation. As mentioned in section 2.1, for every single spot the signal runtime is measured, transformed into a characteristic frequency and finally the equivalent p-wave velocity is calculated by using equation (1) and the well-known thickness of the slabs. Figure 3 shows exemplarily the test results at two different slabs in grid view with coloured zones for different p-wave velocity ranges. The diagram has been generated by linear interpolation between the measured values at single spots.

As supposed it can be stated in general that the total damage zone is significantly larger than the visible spalling and scabbing craters. The difference in p-wave velocity for the surrounding zone compared to undamaged zones is explicit.

Furthermore with IE-tests it can be observed that the characteristics of damage are dependent on a lot of parameters both on behalf of the action and on the behalf of the slab resistance. Important parameters are e.g. the kind and amount of the reinforcement installed, the anchorage of reinforcement steel outside the damage zone, the size effect (crater geometry compared to size of slab) and the foundation of the slab during detonation loading (laminar foundation, single or crosswise span).

An interesting effect observed is that for perforated slabs the surrounding zone tends to be less large than for non- perforated slabs only with spalling and scabbing craters. This might be explained by an energy consideration: In the case of a perforation, a significant part of the kinetic energy remains in the air (blast wave). If there is no perforation, the kinetic energy is dissipated nearly completely by the RC-slab, which leads to more damage in the surrounding material. The same effect has been observed at concrete panels under impact load (see [13]).

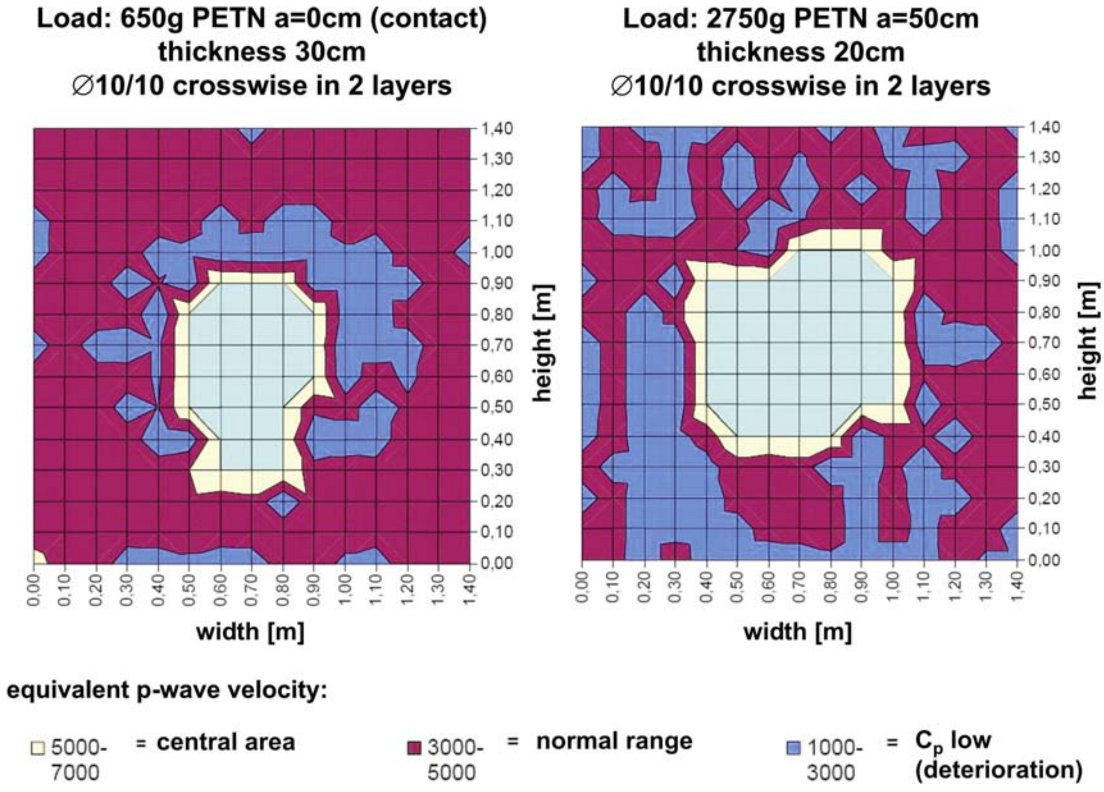

Figure 3: Impact Echo test result for two damaged RC-slabs

3.3 Ground-Penetrating-Radar: test setup and results

Like the IE-tests the GPR testing has been done with a commercial system using a 1.6 GHz antenna for concrete investigations. The measurement has been carried out crosswise as linescans along the axis of a chalk grid applied on the surface of the slab before starting testing. As described in chapter 3.2 the lines of the grid have not been applied directly above the axis of reinforcement bars to get no full signal reflection due to the steel bars.

After the collection of data (signal runtime echoes) in linescan format the data of different lines got migrated into a 3D-data cube with the help of commercial post-processing software. This allows the generation of sectional views in different depth layers.

Figure 4 shows exemplarily the sectional view of a specimen at the position of the upper reinforcement layer. The black part represents the central zone with no GPR data.

The blue zones in figure 4 comply with zones of material with high relative permittivity, i.e. reinforcement bars and their dielectric sphere respectively. It can be observed that in the surrounding zone there is a different relative permittivity which leads to lower signal runtime and displays the deterioration of concrete’s microstructure.

The expressiveness of GPR test results are determined exceedingly by the concrete’s moisture content. This fact can be used in the way that deteriorated zones show higher porosity and more flaws and cracks than undamaged concrete. Consequently moisture permeates faster and deeper into concrete’s microstructure than this would be the case for undamaged concrete.

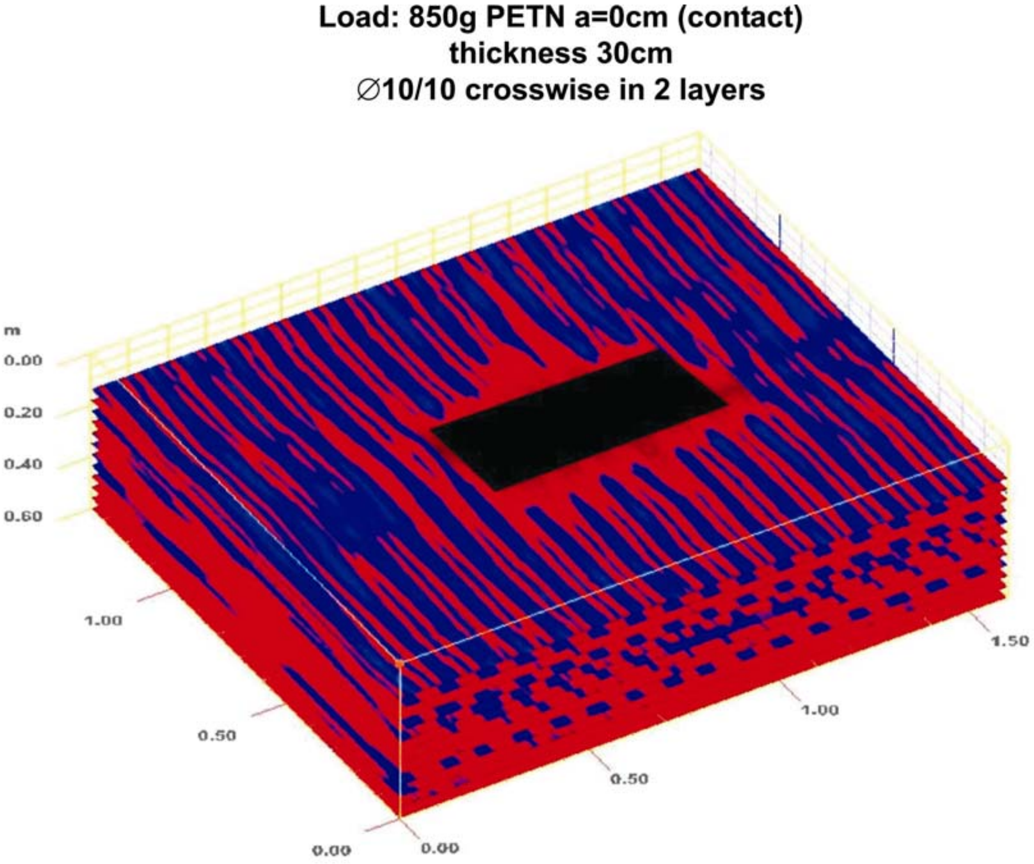

Figure 4: Ground-Penetrating-Radar test result for a damaged RC-slab (3D-View)

Figure 5 shows the cross sectional view of a cut specimen preloaded with contact detonation and stored outdoor. After a short storage in dry climate it can be observed that the deteriorated zone contains more moisture than undamaged parts of the slab. This makes damage detection easier with the naked eye and enhances interpretation of GPR data as well.

Figure 5: Cross section of damaged RC-slab (partly wet) [14]

4. CONCLUSION AND ACKNOWLEDGEMENTS

The NDT-tests carried out at RC-slabs preloaded with contact and near field detonations show, that IE and GPR are suitable methods to determine the size of the total damage zone consisting of visible central zone and the obviously invisible surrounding zone. According to the authors' opinion the Impact-Echo method seems to be more appropriate than the Ground Penetrating Radar system for the presented application because of the direct relation between material properties and the p-wave velocity used by IE.

Referring to the test results it can be stated, that there is a deterioration of concrete in the sur-rounding zone. Because of the great number of parameters both on behalf of the action (e.g. kind, amount and stand-off of explosive, size and velocity of impactor) and on behalf of slab resistance (e.g. kind and amount of the reinforcement, anchorage of reinforcement outside the damage zone, size effect and foundation of slab during detonation loading) a quantitative assessment is hard to do. But the NTD-methods can be used to give a qualitative assessment of the damaged zone for each single case.

Another result of the NDT-test is the adoption that if a perforation is part of the damage the surrounding zone of damage is less extensive than with non-perforated slabs only with spalling and scabbing craters This might be explained by an energy consideration: In the case of a perforation, a significant part of the kinetic energy remains in the air (blast wave). If there is no perforation, the kinetic energy is dissipated completely by the RC-slab, which leads to more damage in the surrounding material. The same effect has been observed at concrete panels under impact load (see [13]).

Additionally to the non-destructive tests presented in this paper destructive tests to gain knowledge about the material properties in the damage zone after accidental load have been carried out (reported about in [15]). Hereby bond failure between reinforcement bars and concrete in the surrounding zone has additionally been observed. Both the results of the NDT-tests as well as the destructive tests help to learn more about damages caused by high dynamic loads and lead to the development of an empirical based model for damage description after high dynamic loading. Therefore a first approach with modified material properties (young's modulus and compressive strength) and a recommendation for bond behaviour in the surrounding zone (range up to 2 times the crater diameter) has been developed (for more details see [15]).

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