STRUCTURAL CONCRETE AFTER HIGH DYNAMIC LOADING - DAMAGE IDENTIFICATION AND REPAIR

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Abstract:

High dynamic loads - for example caused by a vehicle impact, an earthquake or by blast and shock waves due to detonations - lead to damages in RC-structures. Both the damage assessment as well as the repair of damaged reinforced concrete are important topics with respect to a durable use of existing buildings and infrastructure.

The damages caused by high dynamic loads in reinforced concrete structures are characterized by a central zone, 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. To make a statement concerning the structural behaviour of reinforced concrete structures damaged in such a manner, information on the damage is needed. This information is highly necessary to calculate the residual load carrying capacity as well as to repair the damage adequately. To assess the size and quality of the total damaged zone non-destructive tests (NDT) and destructive tests have been carried out on RC-slabs preloaded with either contact or near-field detonations. A further step focuses on the repair of damaged structural concrete. Therefore fundamental investigations concerning the use of different repair methodologies have been carried out with respect to the obviously invisible damage in the surrounding material. The grouting techniques used focus on the repair of concrete’s microstructure and the weakened bond between reinforcement bars and concrete.

This paper includes an empirical model for damage description for reinforced concrete after high dynamic loading based on destructive and non-destructive tests. An approach using modified material properties and recommendations for a modelling of bond behaviour in the surrounding zone is presented. Furthermore the paper contains experiences with the repair of damaged reinforced concrete components by grouting and gives recommendations for the repair of damage after high dynamic loading in general.

1. INTRODUCTION AND MOTIVATION

Accidental loads - for example a vehicle impact, an earthquake 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.

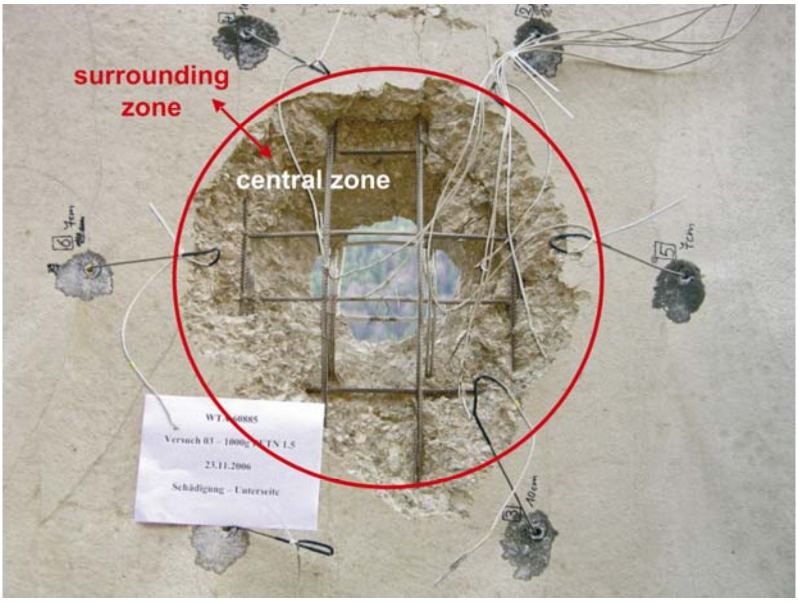


Figure 1: Zones of damage after high dynamic loading

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. To assess the size of the total damaged zone consisting of visible and obvious invisible parts non-destructive (NDT) and destructive tests have been carried out.

A further step focuses on the repair of damaged structural concrete. Therefore fundamental investigations concerning the use of different repair methodologies have been carried out with respect to the obviously invisible damage in the surrounding material mentioned above. The grouting techniques used focus on the repair of concrete’s microstructure and the weakened bond between reinforcement bars and concrete in the surrounding damage area.

All 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 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.

2. DAMAGE IDENTIFICATION

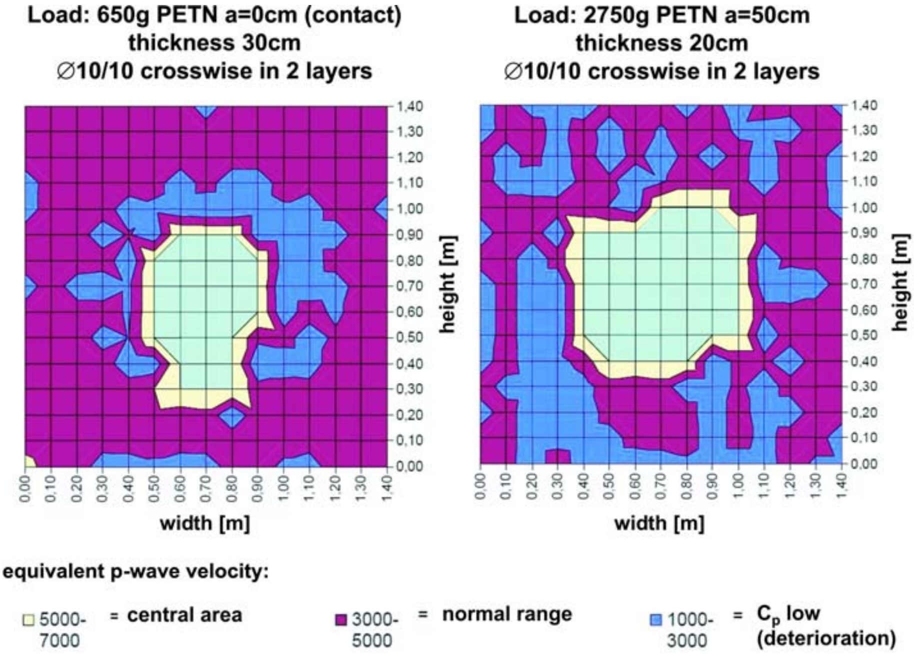
2.1 Non-destructive investigations

For the NDT the use of the acoustical-based Impact-Echo-method (IE) has shown good appropriateness for that particular problem. The history, the principle and the basics of the Impact-Echo-method are explained e.g. by *Sansalone*[1]. For assessing damages in structural concrete with the Impact-Echo-method first 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[2], investigations of voids in tendon ducts of prestressed structures[3], determination of cracks[4,5] and bond quality between concrete and reinforcing steel bar[6]. 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*[10,11] 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 CP 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*[7] for bridge decks loaded at service load level.

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. For every single spot the runtime of the signal is measured, transformed into a characteristic frequency and finally the equivalent p-wave velocity is calculated by using the well-known thickness of the slabs. Figure 2 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.



Load: 650g PETN a=0cm (contact)
thickness 30cm
∅10/10 crosswise in 2 layers

Load: 2750g PETN a=50cm
thickness 20cm
∅10/10 crosswise in 2 layers

Figure 2: IE test result for two damaged RC-slabs

As supposed it can be stated in general that the total damage zone is larger than the visible spalling and scabbing craters. The differential 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 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 [8]).

2.2 Destructive investigations

After investigating the preloaded RC-slabs with non-destructive testing methods destructive tests followed. A profile of the slab starting at the slab centre (=centre of the loading) towards the slab's edge has been generated by cutting up to ten carrots per slab. The carrots as well as the cutting surface first have been investigated visually. Young's modulus and compressive strength of concrete measured at the carrots in the slab's axis destructively are shown over the distance from slab centre in figure 3.

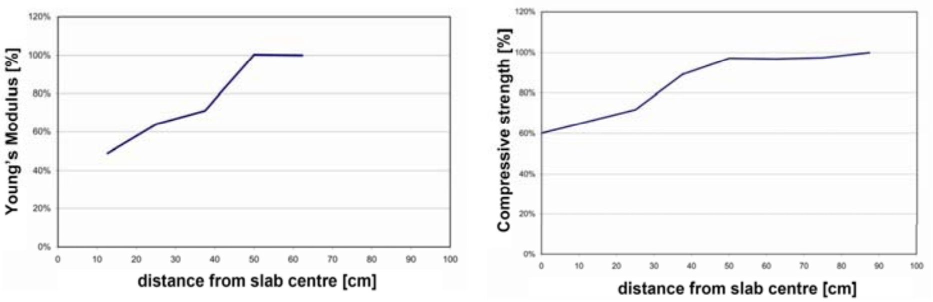


Figure 3: Destructive test results

Furthermore the concrete's microstructure – characterized by porosity and density as derivate of porosity - has been investigated by using the Mercury Intrusion Porosity Method (for more details see [9]).

3. DAMAGE MODEL AND RECOMMENDATIONS

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 and a recommendation for bond behaviour has been developed.

Thus the young's modulus decreases to about 50 % of the value in undamaged concrete, for the whole damage zone the young's modulus should be assumed with < 50 % of the regular value. The compressive strength should be calculated with values of about 60 % of the value in undamaged concrete. These values could be used to make a statement concerning the structural behaviour of RC structures damaged by high dynamic loading and to predict their residual load bearing capacity by calculation. Very important for these issues is the knowledge about the bond behaviour between reinforcement bars and concrete because of its mayor impact on structural behaviour of RC structures. Therefore a recommendation for bond behaviour in the surrounding zone (range up to 2 times the crater diameter) has been developed, which is shown in figure 4 (see [10]).

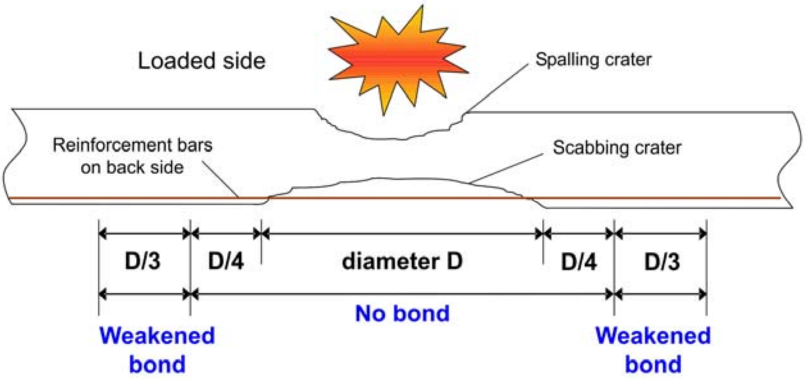


Figure 4: Recommendations according to bond behaviour [10]

4. REPAIR BY GROUTING

4.1 Experimental investigations

A possibility to repair structures damaged by high dynamic loading is to close the cracks friction-locked by injecting them with powder cement suspension or epoxy based resins (EP). As a consequence, the concrete's microstructure and the bond behaviour between concrete and the reinforcement bars are affected. Therefore various fundamental experimental tests with groutings have been carried out (see [11]). To investigate the effect of a grouting concerning the bond behaviour, pull-out tests and uniaxial tension tests have been carried out. These tests show that the bond behaviour of reinforced concrete repaired in this way depends mainly on the success of the grouting and this in turn is dependent on the existing crack width. In general it is to state that the greater the crack width, the greater the success of grouting. The highest increase of bond stiffness could be achieved at a crack width of about w = 0,5 mm. If the crack width is very large (w > 0,5 mm), the increase in bond stiffness is only small even the success of grouting is high. A possible reason for this behaviour at large crack widths may be the non-existence of an interlocking effect of the steel ribs and the concrete at crack widths greater than 2 h_f (height of ribs). To achieve a recognizable interlocking effect, the powder cement suspension used for grouting has got a too low Young's modulus in comparison to concrete. The effect is comparable to the minor bond stiffness of post tensioning tendons embedded into injected mortar within ducts.

Compression and Pull-Out tests with cube specimen repaired by using an epoxy based resin showed also good appropriateness even for smaller crack widths. The increase of uniaxial strength and bond stiffness in comparison to damaged concrete is considerable.

4.2 Recommendations

Additional to the fundamental investigations mentioned above application-oriented tests have been carried out. Therefore the well known RC slabs already been used for damage assessment have been used. Specimens have been repaired by grouting with epoxy resin using a self injector with low pressure. As a result the great variation of damage symptoms characterized by widespread cracking, crack width and branching cracks lead to great uncertainty concerning the grouting success.

But in general grouting techniques seem to be appropriate as repair method for damages due to high dynamic loading. According to the low crack widths existent epoxy resins and grouting techniques with low pressure (< 10 bar) can be recommended to get a save repair and not to damage the structure once more. Nevertheless the success of the repair can not be guaranteed because of the complex crack system in RC structures after high dynamic loading.

5. CONCLUSION AND ACKNOWLEDGEMENT

The NDT-tests carried out at RC-slabs preloaded with contact and near field detonations show, that Impact Echo is a suitable method 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 appropriate for the presented application because of the direct relation between material properties and the p-wave velocity used by IE.

As the test results show, that there is a deterioration of concrete in the surrounding 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 Impact-Echo can be used to give a qualitative assessment of the damaged zone for each single case. The destructive tests show that after accidental load both the material properties in the damage zone are affected as well as bond failure between reinforcement bars and concrete in the surrounding zone occurs. The fundamental experimental investigations of repaired cracked

RC-structures by using an injection of powder cement suspension or epoxy based resin with low pressure show good applicability of these methods. Actually repair tests with full-scale RC-slabs after accidental loading are carried out at the Institute for Structural Engineering at the University of the German Armed Forces Munich.

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