Recent development in blast performance of fiber-reinforced concrete

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Abstract. The paper presents an overview of the recent development in blast performance of fiber reinforced concrete. The paper builds on more than ten years’ history of the research in this field by the team of the Department of Concrete and Masonry Structures of the Faculty of Civil Engineering of the Czech Technical University in Prague.

1. Introduction

1.1. Motivation

Research on the resistance of structures to extreme loading has gained considerable attention in recent years, reflecting the interest in improving the resistance of the civil and transport infrastructure to blasts or impacts. Due to the current geopolitical situation, there has been a considerable increase in the number of terrorist acts. Due to the raised probability of exposure to blast loading, it has become necessary to design government buildings, buildings of significant symbolic value, transport infrastructure, etc., with enhanced safety for users.

This paper presents the findings gathered by the research team from Department of Concrete and Masonry structures, Faculty of Civil Engineering, Czech Technical University in Prague, Czech Republic since the beginning of the research in the field of blast loading on concrete structures in 2006.

The research is based on long-term experimental program of testing the resistance of concrete slab to blast in full-scale. Full-scale experimental program of this magnitude is unparalleled.

Numerical modeling was also performed, but mainly as a tool for evaluating the experimental data and for identifying unmeasurable processes occurring inside the specimen during the experiment. The author’s approach and results in field of computer modeling of blast effects on cementitious composites are also included in the paper.

1.2. The route towards blast-resistant concrete

Concrete is one of the most commonly used building materials due to its high durability, resistance to aggressive environments and relatively low financial cost. It usually has sufficient compressive strength to replace costlier construction steel but its tensile strength is low (only 10% of compressive strength) compared to steel with essentially the same compressive and tensile strength. In past decades many attempts were made to improve the characteristics of concrete so it could be used to replace steel in many other applications. The improvement is usually done by introducing another material into the
Concrete matrix normally consisting of aggregate and Portland cement chemically reacted with water creating a hard matrix binding the other materials together. The first and still the most commonly used approach is to use steel reinforcing bars to provide tensile strength to the structure. However, this approach does not improve the tensile strength of the material. Tensile stresses are transferred to the reinforcement and the concrete surrounding the material usually fails in tension and cracks. The reinforcement holds cracked concrete parts together.

Dispersed reinforcement in form of fibers of various materials was introduced to improve the tensile properties of concrete matrix and it is now being commonly used in structures to reduce risk of cracking of concrete; mainly to ensure required durability of the structure. Concrete commonly used in structural engineering has limited performance when subjected to extreme loads with higher strain rates. This is mainly because concrete is a brittle material with tensile strength much lower than its compressive strength. Fiber reinforced concrete has mechanical properties that enhance its suitability for use in structures subject to high strain rates, e.g. blast or impact loading [1, 2, 3]. The fracture energy value is the decisive material characteristic for an assessment of damage to concrete structures caused by high strain rate loading.

Fracture energy is defined as the amount of energy required to open a unit crack surface area. Fracture energy is a material property, and it does not depend on the size of tested specimen nor the layout of the testing method. Fracture energy of concrete is usually derived from bending tests to total collapse of the specimen. The fracture energy value is equal to the area under the force-deflection diagram (F-δ) recorded during the bending test.

Since 2010, blast experiments have been conducted with basically the same arrangement, using various types and compositions of concrete, ranging from normal strength concrete without distributed reinforcement (NSC) to steel and polypropylene fiber-reinforced concrete (SFRC and PFRC). The results of earlier experiments are presented in [1] and [3].

The focus of the authors then shifted to the use of concrete with even greater strength. The experiments presented in [4] tested two pairs of specimens made of high strength concrete (HSC); both sets were tested with a varying content of high-strength steel (HSS) fibers. Two additional specimens were made of ultrahigh-performance fiber-reinforced concrete (UHPFRC). One of UHPFRC specimens featured a basalt fiber mesh placed in a concrete cover between the soffit of the specimen and the bottom reinforcement. This arrangement, utilizing a mesh commonly used in retrofitting existing structures was used as a basis for the authors’ planned future research in blast retrofitting of concrete structures.

Last sets of experiments conducted in 2015 and 2016 introduced new materials into the concrete matrix of full scale specimens creating extremely heterogeneous structure of the specimen. To the date of issue of this paper, the results from those latest experiments were not yet published elsewhere but this paper.

1.3. Theoretical background to blast loading

To study the behavior of a material subject to a blast loading, it is essential to understand the basic principles of blast mechanics. Blast is a pressure disturbance caused by the sudden release of energy. The energy release may have a number of sources. The most known and usually the most harmful is the detonation of an explosive charge.

The blast loads are created by the rapid expansion of an energetic material, creating a blast wave propagating away from the explosion source. For a distant blast, the flow of air particles caused by expansion of the blast wave creates a pressure load analogous to wind or acoustic load. For analogy of pressure and acoustic load in bridge design refer to [5]. Structures subjected to close-in and contact blast are primarily damaged by the blast wave passing through the structure and reflecting from any material interface.

All the types of blast loading were studied by the authors’ research team. Special attention was paid to the propagation of shock waves through air and interaction between passing shock wave and concrete blast barriers, see [6, 7, 8].
Further and more detailed description of mechanics of blast loads as well as the physics description of blast phenomena can be found in [9] and [10].

2. Experimental program

Full-scale testing is the most accurate method for determining the blast resistance of a complex heterogeneous material such as concrete or other cementitious composites. Although the current state-of-the-art numerical modeling can provide reliable data on blast loading, it is difficult to calibrate a material model without a prior experiment and subsequent optimization. The authors used their experience in field testing, and decided to conduct full-scale experimental program focused on the blast resistance of concrete bridge decks.

The main full-scale experimental program gradually evolved in correspondence with the shift of author’s focus from the study of standard RC structures to the study of behavior of complex composite materials. Experiments conducted in 2015 and 2016 tested highly heterogeneous concrete-based materials with promising results.

A reduced-scale experimental program was designed to supplement the costly full-scale experimental program and to characterize the effect of size of aggregate relative to size of a structure and the effect of reinforcement ratio of the structure. The reduced-scale experimental program was extensive. Multiple types of concrete were tested.

2.1. Full scale experimental program
The experiments were performed in the Boletice military training area, in cooperation with the Armed Forces of the Czech Republic. The location and the layout of the experiment remained practically same during the years, though some improvements were gradually made to the layout.

The specimens were concrete slabs 6 m in length, 1.5 m in width and 0.3 m in thickness. The steel reinforcement remained the same in all the experiments. It consisted of 11 pcs 16 mm dia. reinforcing bars every 140 mm on both surfaces, 10 mm dia. bars every 150 mm as an outer transverse reinforcement. Shear reinforcement was provided by 8 mm dia. links (9 pcs/m2). Concrete cover of 50 mm was taken to the outer surface of the transverse reinforcement. All full-scale specimens were reinforced with standard steel bars with characteristic yield stress of 500 MPa.

2.1.1. Layout of the experiment. The scheme and the layout of the experiment are shown in figure 1 and figure 2. The ground beneath the slabs was excavated to a depth of 2 m to avoid the results being influenced by the shock wave bouncing off the ground. 25 kg TNT charges were placed on steel chairs in the middle of each slab. The chairs provided 450 mm standoff from the slab.

![Figure 1. Layout of the experiment](image)

2.1.2. Instrumentation of the experiment. The response of the specimen was recorded with a high-speed camera with a frame rate of 15,000 frames per second (fps). The additional lighting of the scene required for high-speed photography was provided by aluminum powder ignited by a small charge of...
plastic explosive. The camera observed the spall formation on the soffit of the specimen through an angled mirror (see figure 3). This thesis is not focused on instrumentation of the experiment. For detailed information on the instrumentation used during the experiment refer other author’s papers [11, 12, 13].

2.1.3. Materials of the specimens. Many variations of composition of concrete were tested during the years. The experiments started in 2010 with specimens made of standard concrete class C30/37 according to Eurocode. In 2011, dispersed reinforcement in form of polypropylene (PP) fibers was used. Concrete strength reached up to 80 MPa.

Low strength steel fibers (yield strength 350 MPa) were added to the concrete matrix of tested specimens in 2013 to study the influence of increased tensile strength and fracture energy of concrete on its resistance to blast effects.

To further improve the behavior of concrete, high strength steel fibers (yield strength 2200 MPa) were used in 2014. Compressive strength of concrete varied from 60 MPa to 130 MPa depending on the amount of fibers, amount of cement and overall composition of the matrix.

To follow the route of gradual improvement of performance of concrete, recent experiments introduced additional materials to the concrete matrix to dramatically increase the heterogeneity of the material. In addition to the dispersed steel fiber reinforcement, a further reinforcement in the form of a basalt mesh (30 x 30 mm) was placed in the concrete cover at 25 mm distance from the soffit of some specimens. Other specimens included multiple layers of the basalt mesh evenly spaced along the depth of the specimen.
The melting point of the basalt fibers is 1350 °C. The tensile strength of the basalt fabric was about 4200 MPa with a tensile modulus of elasticity of about 85 GPa. The unit weight of the mesh is 250 g/m² with weight density of 2.67 g/cm³. The minimal tensile strength of the basalt fiber is 700 mN/tex, the minimal tensile strength of the unit width of the mesh is 50 kN/m. Each string of the mesh consists of multiple fibers so the diameter of each string cannot be accurately defined, but required for FEM modelling. From parameters presented above, an effective area of each string equal to 1.4 mm² was calculated instead.

The most recent specimens tested in 2015 and 2016 also included a different approach to increasing the heterogeneity of concrete. Recycled textile sheets were introduced to create disturbance to the propagation of shock waves through the specimen. The goal was to try to increase the ability of concrete to dissipate blast energy. A typical concrete element in form of a hollow-core prestressed panel was also tested with the same boundary conditions to provide the direct comparison of behavior of specimens specially designed to withstand effects of a blast and the behavior of a typical concrete structure. Cross sections of the specimens with drastically increased heterogeneity are shown in figure 4 to figure 6.
2.1.4. Results of the experiment. The effects of blast loading on the top and bottom surfaces of the specimens after each test were documented. Residual deflection of each specimen was also measured. Damage of selected specimens is shown in following figures. For detailed description and discussion of results refer to a corresponding authors’ published paper.

![Figure 7. Damaged specimen No. 1 after the blast (60.1 MPa compressive strength, no additional reinforcement) – top view (left) + bottom view (right)](image)

![Figure 8. Damaged specimen No. 15 after the blast (76.1 MPa compressive strength, 80 kg/m³ of high strength steel fibers 30 mm long) – top view (left) + bottom view (right)](image)

![Figure 9. Damaged specimen No. 16 after the blast (129.5 MPa compressive strength, 160 kg/m³ of high strength steel fibers 13 mm and 30 mm long) – top view (left) + bottom view (right)](image)
2.2. Reduced scale experimental program

Full scale experiments are very expensive and time & space demanding. It was decided to verify, whether the material properties influencing the blast resistance of a specimen can be studied on reduced scale experiments. Some of the results presented in this section were already published in [14].

2.2.1. Materials of the specimens. Two sets of reduced scale specimens were created. First set used standard concrete mixture, the second set used micro-concrete. The same amount of steel reinforcement was used for both materials. The amount of steel bar reinforcement of reduced scale specimens was derived by reducing the cross sectional area of the longitudinal reinforcement roughly by the scaling factor.

The use of micro-concrete model for simulation of behavior of concrete structures during the earthquake simulation test seems to be common in earthquake experiments. Micro-concrete seems to have the ability to simulate standard concrete quite well in elastic stage, but because of the difference in material properties between standard concrete and micro-concrete, especially the nonlinear stress-strain relationship, the prediction of nonlinear behavior of the structure remains questionable.

Micro-concrete, to the authors’ best knowledge, has never been used in reduced scale experiments to simulate the behavior of full scale concrete structure exposed to blast loading. The use of micro-concrete, if proven applicable, could allow testing the blast resistance of concrete structure in reduced scale and thereby greatly reduce cost of the experiment. Compared to an earthquake, the effects of blast on structure are much more complex. The strain rate dependent non-linear behavior is influenced by propagation of the shock wave through the structure and its reflections from interfaces between the heterogeneous materials within the concrete matrix, i.e. cement mortar, aggregate and reinforcement. Because of this phenomenon the comparison of performance of micro-concrete and full scale concrete subjected to blast loads has to be studied in detail.

2.2.2. Results of the experiment. At first glance, the results of full scale experiment (for example Fig. 4.11) show certain similarities to the reduced scale experiment, but there are also multiple key differences in the specimen damage. A further study of the influence of the scale reduction and composition of concrete on the results is definitely needed.

Typical damage of a standard concrete specimen is shown in as well as typical damage of a micro-concrete specimen is shown in figure 10. The results obtained from micro-concrete specimens show very similar damage mode as previous results. There are differences in spalled areas of each specimen. The size of spalled area varies depending on the amount of steel reinforcement. The amount of reinforcement in the soffit of the specimen seems to have the greatest impact on specimen damage. The amount of top reinforcement seems to have no significant effect.

![Figure 10. Blast damage to standard concrete specimen (left) and micro-concrete specimen (right) after the reduced scale experiment.](image)
The comparison of results of full scale and reduced scale experiments with standard concrete specimens shows that the basic mode of damage is present in both cases. But closer look suggests that the behavior of concrete between reinforcing bars is different. The reason of the difference is the use of the non-scaled concrete matrix. It is necessary to maintain the same ratio between the reinforcement and aggregate to obtain results that correspond.

3. Numerical simulations
Computer modelling was widely used during authors’ research throughout all the topics that the authors have studied. It is documented in authors’ published papers.

3.1. Purpose of the computer modeling
Computer modeling of shock wave propagation in air served as a tool to design effective blast barriers for use in public buildings, see [6], [7] and [8]. Computer modeling of shock wave propagation in cementitious composites was conducted mainly to supplement experimental results and to identify and quantify various physical phenomena that cannot be measured directly during the experiment. For further information, refer [1], [3] and [4]. FEM model was mainly used to identify and visualize the processes occurring in the specimen directly after the detonation. Currently, it is impossible to directly capture the behavior of specimen in the short timeframe of a blast load. Even high-speed camera recording is problematic due to numerous difficulties caused by the rapid release of blast energy.

Numerical models of the full-scale experiments, mainly focused on the effect of material heterogeneity of the structure, were developed for evaluating the experimental results. The model setup process is described in the following text. The numerical model and the material models of the concrete were calibrated according to the outcomes of the experiments described in the previous section.

3.2. Approach to the computer modeling
The LS-DYNA solver was used for non-linear analysis of the experiment. The software is based on the finite element method (FEM) either in implicit form or in explicit form. It also allows the creation of finite element meshes of elements defined by various mathematical formulations and their combinations to create mathematical models for various types of materials and loadings. The layout of some typical computational models and results is shown in the following figures.
Figure 11. Overpressure at the front of passing shock wave at multiple standoff distances with and without a barrier.

Figure 12. Pressure contours at the cross section of the full scale specimen 0.25 ms after the detonation. See the apparent pressure concentration near the stirrup caused by the reflection of shock wave of the interface between two materials with significantly different densities.

Figure 13. Reduced scale FEM model damage compared to the experiment.
4. Conclusions
Conclusions from each of the sub-topics studied by the authors’ research team can be found in corresponding published papers. This section includes only the most significant findings and remarks for future research in the field of blast resistance of concrete structures.

The blast performance of reinforced concrete specimens increases with the addition of high-performance steel fibers and with an increased volume of high-performance steel fibers. By contrast, the addition of low-performance steel fibers has no significant effect. Increasing the fiber content and the compressive strength of fiber concrete up to ultrahigh-performance fiber concrete further enhances its blast performance. None of the UHPFRC specimens was noticeably breached during blast loading, whereas all the SFRC, PFRC and RC specimens were breached.

A basalt mesh inserted into the concrete cover at the soffit of the UHPFRC specimen improves its blast performance, as expressed by the area of spalling and by the volume of debris. The UHPFRC specimen with a basalt mesh experienced a larger extent of internal damage than the regular UHPFRC specimen. This phenomenon was studied numerically, and it was proved that the cause is the internal rebound of the blast overpressure, which interacts with further propagating blast overpressure waves.

In addition, numerical modelling identified the importance of another effect: the stress concentration on the interfaces between materials of different densities. This is caused by the rebound of the shock wave. In the case of a standard bar reinforcement, the stress concentration may weaken the bond between the concrete and the reinforcement, and may seriously affect the overall behavior of the structure.

The effect of stress concentration may also contribute to the delamination of a composite material. This delamination is not necessarily an issue; it can provide benefits to the overall blast performance of the specimen. For example, when the entire cover (50 mm in thickness) becomes disconnected from the specimen after the explosion, it is ejected to the surroundings and can cause damage to people or equipment. When a basalt mesh is used within the cover layer, it can reduce the volume of debris ejected from the specimen to zero, or it can at least decrease its initial velocity and thus reduce its range and kinetic energy. In fact, the increased delamination and increased deformation of the concrete cover can be very effective in dissipating the energy of the blast wave. The formation of a massive horizontal crack across a wide area requires a lot of energy. In combination with the subsequent plastic deformation of the cover layer restrained by the basalt mesh, a large amount of blast energy is mitigated within the structure of the panel.

Based on the results obtained so far, the research team is currently focusing on similar topics based on the observations made during the research presented in this paper, including:

- Behavior of highly heterogeneous concrete composites with controlled heterogeneity subject to close-in explosion
- Behavior of structures made of concrete and concrete-based composites to extreme loading caused by contact explosion
- The study of combined effect of multiple extreme loads acting together, e.g. explosion with subsequent fire, fire with subsequent explosion, high speed impact followed by explosion and fire etc.

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