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Dynamic bearing capacity of ductile concrete plates under blast loading

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ABSTRACT

For chosen infrastructural buildings, the occurrence of an intentional or accidental blast loading has to be considered. These infrastructures building components have to withstand the loading in order to avoid fatal debris ejection and to ensure the integrity and stability of the construction under such extraordinary loading situations. To ensure a sufficient resistance in a slender construction, advanced concrete based materials are known to have high protection potential (i.e. Roller 2013). This paper investigates systematically the bearing resistance of plate elements made of the ductile concrete DUCON® under blast loading conditions. Therefore, a series of shock tube tests has been conducted to investigate different configurations of ductile concrete plates with varying thickness and degree of reinforcement. Based on the results, a mathematical description of the resistance behavior of ductile concrete has been derived. Iso-damage curves are calculated using the derived resistance function in a Single-Degree-of-Freedom model. Applying similarity analysis for non-dimensionalized formulation enables the transfer of the experimental results to arbitrary (similar) plate dimensions. Results and findings of the paper are finally compared and discussed in relation to normal strength reinforced concrete.

1. Introduction

The protection of critical buildings (malls, governmental buildings and embassies), infrastructures and utilities, train and subway stations against damage, destruction or destruction by deliberate acts of terrorism, criminal activity and malicious behavior is an important task to ensure open and resilient societies. Furthermore, today's aspiration in architecture is to create slender and filigree constructions which are also flexible in their usage. Hence, modern designs and dimensioning of structures always need to be a compromise between competing requirements.

To fulfill the requirements of a sufficient protection level on the one hand and a slender component design on the other hand, innovative building materials with an increased bearing capacity under the considered loading cases are quite interesting.

Reinforced concrete with an increased ductility offers the possibility to raise the resistance for dynamic loading situations [1–3].

Ductile concretes as for example the DUCON® product have proven their potential in independent test series conducted over the last years especially under contact and close in detonation scenarios [4–6].

The ductile concrete (in the following also abbreviated DC) offers the possibility to adjust the resistance behavior within a certain range to the type and amplitude of loading not only by plate thickness and conventional reinforcement but also by degree MicroMats® reinforcement. As a basis for the following investigations, the bending behavior of the regarded ductile concrete configurations was studied in static four point bending tests. The main experimental work presented in this paper was conducted to systematically investigate the dynamic load bearing capacity of DC plate elements under a far field blast loading orthogonal to the panel axis. Therefore, a triple series of shock tube tests was conducted in which the thickness of the ductile concrete elements and the degree of micro reinforcement was varied. The configuration of the static and dynamic test and results of these tests are presented in Section 2 of the paper.

Furthermore, dimensioning of the wall requires predictive capabilities of the dynamic response for given plate types and geometry, span conditions and relevant blast loading scenarios. Finite element calculations offer detailed insight but are expensive

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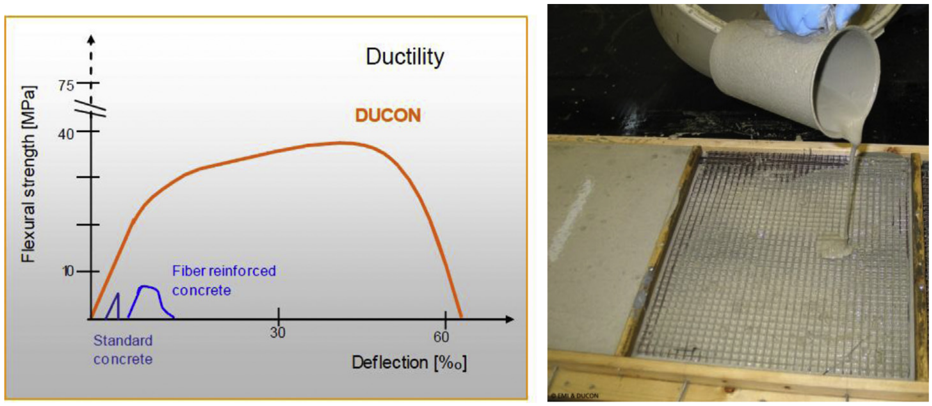

Fig. 1. Performance potential of DUCON(©), high ductility (left), fabrication process of DUCON (right).

with respect to necessary time and expertise. Hence, a simplified model is needed for quick prediction of the structural behavior.

Single-Degree-of-Freedom (SDOF) models are a promising simplified approach for building elements under blast loading [7,8] with well proven prediction qualities. Numerous different applications can be found in literature, for example on concrete walls and slabs [9,10] or long-span girders [11]. A further review of literature can be found in Section 3.1. Key parameters to calculate qualitatively good predictions are the adequate description of the potential non-linear elastic–plastic resistance of the mentioned component in terms of a mathematical relation between the force and corresponding displacement. Within this paper, two different methods for the derivation of this resistance function are presented and discussed. On the one hand, key parameters of the resistance function are determined using inverse analysis of the experimental results. On the other hand, simplified analytical formulas are derived for the same input parameter based on static force resistance parameters of the material. An alternative method for derivation of the resistance functions just based on nonlinear structural mechanics has been neglected in order to keep the complexity of the paper within a reasonable range, but it is focus of future work. Using the derived resistance functions, iso-damage curves are calculated, whereby also a non-dimensional expression is derived and verified in chapter 3.

Finally, the derived bearing capacity against dynamic blast loading is compared to the resistance of normal strength reinforced concrete and ultra-high performance concrete in pressure–impulse diagrams. Results of this comparison are presented and comprehensively discussed in Chapters 4 and 5.

2. Material characteristics and experimental investigations

In order to describe the load bearing capacity of ductile concrete plates against blast loading, a two stage experimental investigation program was conducted for three common DC configurations.

In a first step, the basic load bearing capacity of the three plate configurations was tested in static four points bending tests. Goal of these tests was to determine the bending tensile strength and ductility. Furthermore, a series of shock tube test was conducted in order to determine the dynamic bearing behavior of the plates under blast loading with significant dynamic strain rates.

2.1. Material characteristics

DUCON representing one market-available ductile concrete used for the following investigations is a composite made of self-compacting high-performance concrete and a spatial micro reinforcement (MicroMat®) which can optionally be combined with common steel bar reinforcement [12]. The basic concept is thereby to increase the ductility of the high-performance concrete matrix by adding the spatial orientated micro reinforcement instead of probabilistically distributed steel fibers.

A key characteristic of the DUCON product is not only higher strength in tension and compression, but also a significantly increased performance in the energy absorption potential, the impact and abrasion resistance as well as in the durability and freeze-thaw resistance in comparison to standard concretes and other high performance concretes [13,14]. In addition, ductile concrete in general features an extremely ductile material behavior with a high degree of plastic deformations before ultimate failure, see Fig. 1.

The high strength infiltration mortar itself has a compressive strength f_{cm} of 100–130 MPa and a Young's modulus of 38,000 MPa.

The reinforcement of DC is realized by layering of the micro-mats, which are interconnected to a 3 dimensional mat-system and consist of welded wires. The degree of reinforcement is mainly regulated by the mesh size of the mats and the wire diameter and amounts to 2.8 Vol-% per tensile direction for standard configuration. Corrosion resistant grid layers can be included to avoid corrosion on the surface of the components. The welded micro-mats can be realized using either a ductile normal strength or a high strength steel. The general material parameters of the two steel configurations are shown in Table 1. The wire diameter of the mats varies for ductile concrete between 0.3 and 1.5 mm. Generally, the use of structured mats instead of unstructured fiber distributions results in a 2-D distribution of loading capacity, which is an essential difference compared to the other concrete materials.

The fabrication of a ductile concrete is illustrated in Fig. 1. The liquid self-compacting mortar is poured into a wire mesh designed form. Depending on the application, the plasticity of the cement can be modified. Based on the high flowability of the self-compacting concrete, no vibration and compaction plus leveling of the surface is necessary. Despite the high steel volume fraction of

Table 1
Material parameter of the micro-mat steel reinforcement.

Steel material	Tensile strength f_{tm} [MPa]	Ultimate failure strain ε_{su} [%]	Young's modulus E_s [MPa]
Normal strength, welded	350–400	17–20	205,000
High strength, welded	750–850	1.5–3.0	205,000