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Experimental and numerical studies on the structural response of normal strength concrete slabs subjected to blast loading

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ABSTRACT

To assess the blast performance of concrete structures, a shock tube has been used to simulate blast loading against concrete slabs of two different mixes ordered as C45/55 and C20/25. The C45/55 slabs were tested without reinforcement, whereas the C20/25 slabs were tested both with and without reinforcement to investigate the effect of adding steel bars on the structural response. The performance of the shock tube itself was also evaluated. Compression tests on cubes and cylinders of both concrete recipes were performed to obtain material input data for numerical simulations. Numerous compression tests were also conducted using the C20/25 mix to obtain insights into the statistical variation in the material properties as concrete is inherently heterogeneous at the macroscopic level. In addition, tensile splitting tests were conducted on both materials. The shock tube tests show that the boundary conditions are important and that the reinforcement will direct the crack pattern. Fluid-structure interaction (FSI) effects are not dominant for this particular problem, because the concrete slabs suffer relatively small deformations before through-thickness cracks appear. Once cracks extend through the thickness, FSI effects may become influential, but it appears that when this occurs there is little or no residual capacity left in the slabs. Numerical simulations were used to investigate the influence of various parameters, revealing that the results are highly dependent on the boundary conditions and particularly on the tensile strength of the concrete. It was found necessary to model the entire clamping assembly to recreate the experimental observations.

1. Introduction

Concrete is one of the most widely used construction materials, and due to its versatility in shape and form, relatively low price, structural properties and abundance, it will continue to be so for the foreseeable future. However, the low tensile strength of concrete warrants the use of steel reinforcement. One of the most recent ideas for using reinforced concrete is for submerged floating tunnels (SFT) [1], a concept deemed viable by several feasibility studies [2,3]. Although analyses of such structures have been performed [4–6], no such structure has ever been built in full-scale. As a part of the project that aims to make the Norwegian coastal highway route E39 ferry-free [7], an SFT has been suggested as a means of crossing some deep and wide fjords. One of the concerns for an SFT is the case of an accidental explosion inside the tunnel, for instance, from a collision involving a tanker carrying flammable goods. Naturally, one cannot perform a full-scale test of such a massive construction, thus, one has to utilise smaller components and finite element (FE) simulations. This study aims to investigate the behaviour of concrete slabs subjected to extreme loading conditions of the type arising from a blast load. A shock tube facility [8] has been used to generate the load on the slabs, and an important part of this study is to assess the test rig's performance and suitability for use with concrete specimens and assess the qualitative performance of FE models.

With blast loading due to terrorist attacks also being an increased concern [9], expanding the database of experimental results in this field is important – both to obtain a better understanding of a structure's behaviour due to such loads, and for the verification and validation of numerical models aimed at handling this complex problem. The seminal work by Kingery and Bulmash [10] has been essential for determining load parameters, and has naturally been used in several studies [11–14]. A more general review of blast loaded plates can be found in the work by Rajendran and Lee [15].

Concrete slabs subjected to blast loading have been increasingly studied with various approaches [16–19]. Full-scale field tests on

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concrete slabs have been conducted by Schenker et al. [20], who found that aluminium foam added to the concrete structure may have positive blast mitigation properties. Fibre-reinforced concrete is typically used for that purpose [21,22], and even the aggregate can be augmented to that end [23]. Retrofitting concrete slabs with fibre-reinforced concrete may also improve the structure's blast performance [24]. Fibres can also improve the capacity of columns exposed to blast loading [25,26]. This naturally applies to slabs as well [27], but conventional reinforcement is still important for the post-blast static behaviour [22]. A review of fibre-reinforced concrete subjected to dynamic loading has been performed by Soufeiani et al. [28].

The shock tube technique is a well-established approach used to simulate blast loading against structures [29,30]. The appeal of shock tube experiments rather than using explosives – where even the charge orientation may influence the results [31] – is that the produced loads are consistent and the boundary conditions are well defined. Toutlemonde et al. [32] considered shock tube testing of concrete slabs to be a realistic structural test that can be used to validate e.g. design codes. Further testing of simply supported concrete slabs [33] showed that rapid loading may trigger a shear mechanism rather than bending, which could cause earlier failure compared with quasi-static bending. One-way slabs made from different types of concrete with various reinforcements were tested by Thiagarajan et al. [34] and replicated numerically, where mesh sensitivity proved to be an important issue when concrete is exposed to extreme dynamic loading conditions. Concrete structures exhibit a sensitivity to the load rate, a topic that is highly studied and debated [35–42]. An investigation into rate effects in concrete is beyond the scope of the current study, although it will be mentioned in the context of blast loading.

This study consists of an experimental part and a numerical part. The main experimental objective is to determine the blast load capacity of concrete slabs using a shock tube. Two different concrete mixes ordered as C45/55 and C20/25 were used to cast slabs, where the former mix was tested without reinforcement, and the latter was tested both with and without reinforcement. An estimate of the pressure at which the slabs suffer through-thickness cracks is made for the different material configurations. A battery of standard concrete material tests were carried out to verify that the concrete mixes possessed the mechanical properties as ordered. Potential fluid-structure interaction (FSI) effects during shock loading and the effects of boundary conditions are discussed, and the use of 3D digital image correlation (3D-DIC) as a deformation measurement tool is assessed. The shock tube as a means of generating blast loads against concrete components was also verified. The experiments are captured using two Phantom v1610 high-speed cameras which are synchronised with the pressure recordings in the shock tube.

Finally, the numerical part of this study investigates to what extent a standard commercial FE software (LS-DYNA [43]) is able to reproduce the experimental results. The K&C model [44,45] was chosen based on its ease of use and applicability to model blast load scenarios [17,31,34,46]. Different ways of modelling the boundary conditions were evaluated, and the effects of altering different material parameters were studied. In general, the numerical simulations gave good qualitative results.

2. Material testing

2.1. Concrete

A list of the main constituents in the concrete mixes ordered as C45/55 and C20/25 is presented in Table 1. A set of common quasi-static concrete tests (cube compression, cylinder compression and tensile splitting) was conducted to assess the mechanical material properties of the two concrete materials. Cubes with side length 100 mm were used, while the cylinders were 100 mm in diameter and 200 mm in length. The compression tests were carried out in a fully automated Toni Tech 3 000 kN load controlled apparatus (load rate 0.8 MPa/s), while the tensile splitting tests were performed in a Mohr/Federhaft/Losenhausen BP-300 compression rig (load rate 0.6 MPa/s). The tests provided the cube compressive strength f_c, the cylinder compressive strength f_{cc}, and the estimated tensile strength f_t based on the design code [47]. The mass densities ρ_c were also measured. Each test was repeated three times, except for the tests on the C20/25 concrete which was repeated 20 times (after 28 days of curing).

Table 1
Constituents of concrete recipes given in weight percentage.

Concrete mix	Water	Cement	w/c ratio	Aggr. 0–8 mm	Aggr. 8–16 mm	Total
C45/55	7.4 %	19.3 %	0.387	43.1 %	30.2 %	100.0 %
C20/25	8.0 %	12.9 %	0.621	50.1 %	29.0 %	100.0 %

Table 2 lists the average values and standard deviation from the tests. The results show that the concrete ordered as C45/55 meets the requirements for the classification. For the C20/25 concrete, the cylinder and cube compressive strengths were 39.6 MPa and 46.3 MPa, respectively. A more accurate classification would be C30/37 according to [48], so this result shows that what is ordered is not necessarily what is received and underscores the importance of conducting material tests. For consistency throughout the study, the initial denomination (C20/25) has been retained for this concrete mix.

2.2. Steel

The steel reinforcement used herein is a standard off-the-shelf grid of smooth circular steel bars (initial diameter $D_0 = 2.6$ mm) connected with spot welds at centre offsets of approximately 72 mm in both directions, thereby forming a regular quadratic net. In total, 12 specimens used for tension tests were cut from the net – 6 in each direction of the net. Two of the 12 specimens (one from each direction) were cut such that the weld became part of the gauge area during testing, while the remaining 10 specimens were cut from between the welds.

Engineering stress and engineering strain from quasi-static (estimated initial strain rate of $3.6 \cdot 10^{-4}\ \mathrm{s}^{-1}$) tension tests on the steel bars are plotted in Fig. 1, with the specimens from the 0° direction to the left and those from the 90° direction to the right. Included in Fig. 1(a) is the bilinear material model used for the reinforcement in the numerical simulations in Section 4. The average yield stress defined as the stress at 0.2% plastic strain, and its standard deviation, were calculated to be 766.4 ± 13.6 MPa. Based on the tension tests, Young's modulus was calculated to be 210 277 ± 9 669 MPa. The fracture strain ε_f after testing was obtained by measuring the diameter D_f at the root of the neck, enabling the calculation of $\varepsilon_f = 2\ln(D_0/D_f)$ – which resulted in $\varepsilon_f = 0.880 \pm 0.041$.

3. Component tests

A shock tube facility was used to test concrete slabs cast from the C45/55 and C20/25 concretes described above. In addition to assessing the performance of the shock tube, a main objective was to observe how the slabs behaved when exposed to increasing shock loads, as well as to estimate the overpressure at which through-thickness cracks appear. For the C20/25 concrete, reinforcement was added to some of the slabs to determine the influence of adding steel bars on the crack pattern and deformation. The reinforcement grids were placed with an approximately 7 mm offset from each surface, making the distance between their centres approximately 36 mm.

To maintain good control of the geometry, the concrete slabs were cast in a custom-made wooden mould (see Fig. 2) designed according to the shock tube dimensions, as suggested by Toutlemonde et al. [32]. Smooth lubricated plastic tubes were inserted through the bolt holes to