A preliminary investigation for accidental load design of a submerged floating tube bridges

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ABSTRACT

Submerged floating tunnels are more and more considered as a suitable solution to cross water channels limiting environmental impact on the visual landscape and ensuring large ship passage while crossing large distances between coasts. The design of this kind of strategical infrastructures must deal not only with live loads and particular loading conditions coming from the floating situation, but needs also to carefully consider accidental actions that concur to the global safety of the infrastructure. The construction of the new E39 highway along the Norwegian coast asks for crossing several fjords and this solution is seriously taken into consideration. For this reason, a comprehensive research program was aimed at the analysis of accidental load design of the infrastructure. This paper aims to present a comprehensive overview of an ad-hoc experimental investigation on the behavior of reinforced concrete (RC) circular slabs (60 cm diameter) under exposure to fire, blast, or a combination of both actions. Additionally, it seeks to draw design-driven conclusions that could be valuable for the design of critical infrastructure in scenarios involving fire and blast. The presented experimental campaign was intended to provide a benchmark for assessing the reliability of the design approaches to be adopted in the design of the global infrastructure. First of all, the concrete mechanical characterization at normal conditions and at high temperatures was performed referring both to uniaxial compression and uniaxial tension. The structural behavior of simply supported RC slabs has also been investigated by considering slabs exposed to a hydrocarbon fire curve at different exposure times and by considering the post-fire application of static or dynamic loading condition. In particular, the fire curve was applied by a gas burner while the dynamic load was reproduced by a shock tube equipment that was used to apply two different blast-like pressure histories.

KEYWORDS: *Submerged floating tunnel; Concrete mechanical properties; Fire exposure; Blast loading; Fire-blast interaction*

1. Introduction and research significance

Reinforced concrete (RC) structures represent the major part of today's infrastructure, for example in bridges and tunnels. In addition to the normal design loadings, RC structures may be exposed to extreme hazards throughout their service life, including accidental actions (fire exposure and blast as a consequence of fire in case of goods transport), natural disasters (earthquakes) or even terrorist attacks (Zhang et al. 2019, Ruan et al. 2015).

In the case of tunnels, the consequences of extreme events can be even worse due to the relative closedness of the structure, especially concerning the effects related to fire exposure which is often regarded as the main physical threat in their design. An explosion after a fire exposure may lead to potentially disastrous consequences, easily aggravating the damage in the structure or even causing the complete collapse (Zhang et al. 2019, Colombo et al. 2021). The investigation of the combined action of fire and explosion loads in tunnels is of great interest also for the Norwegian Public Roads Administration's (NPRA) E39 coastal highway route project. This project is aimed at establishing an improved, and potentially ferry-free, highway route between Kristiansand to Trondheim along the Norwegian west coast, reducing the travel time by half (Stensvold & Minoretti 2014). To do so, this pioneering project needs asks for alternative solutions to be considered, as for example floating bridges or submerged floating tunnels also known as submerged floating tube bridges (SFTB) (Minoretti et al. 2020).
The assessment of a complex structure under an extreme load condition typically requires advanced numerical models. These models often need to be validated comparing their predictions with the results from experimental tests. The experimental findings of this study are therefore valuable to define a reliable benchmark for numerical models which, with numerical upscaling, will be instrumental for the design of the SFTB under exceptional load conditions, such as the combined action of fire and subsequent blast loading.

2. Experimental campaign overview

This study experimentally investigates the combined effect of fire exposure and blast loading on RC slabs. Figure 1 shows the research strategy for the investigated case scenario, illustrating the scope of this study within the background project and the future research.

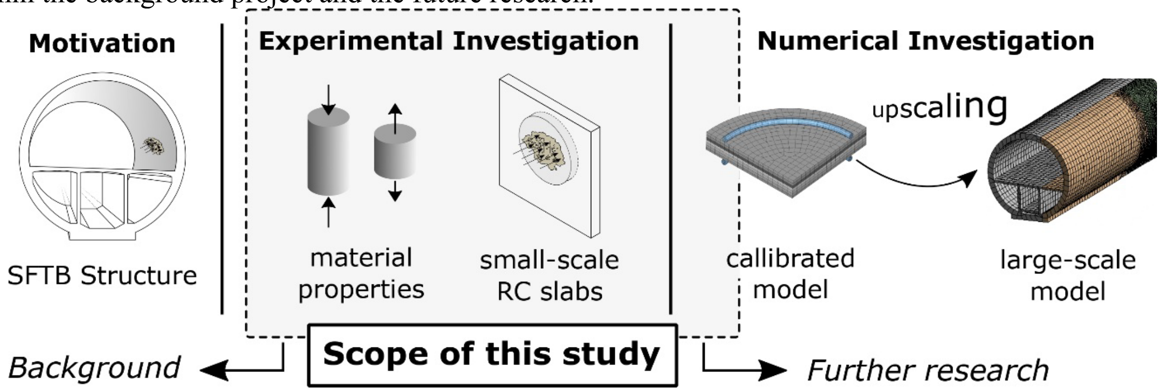


Figure 1: General overview of the research

The material considered is a concrete of grade C45/55 which today represents typical concrete used in Norwegian infrastructures under exposed conditions. Polypropylene microfibres were also added into the mix (1 kg/m3) to prevent explosive spalling. The structural elements investigated consist of reinforced concrete circular slabs, 70 mm thick, with a diameter of 690 mm. Two layers of bi-directional B450 steel reinforcement (Ø6/60 mm) were positioned with a net concrete cover of 10 mm.
The overall experimental campaign is made of three different phases:

- Material characterization after exposure to high temperature (Arano et al. 2023b)
- Static bending tests on slabs exposed to fire action. (Arano et al. 2023a)
- Bending tests of slabs exposed to fire action and loaded with shock wave. (Colombo et al. 2021)

3. Material properties at high temperatures

The effect of elevated temperatures on the mechanical behaviour of concrete was experimentally investigated on concrete cylinders in residual conditions, after a single thermal cycle at different elevated temperatures (200, 400 and 600 °C) (Arano et al 2023b). The obtained compressive and tensile constitutive response of concrete are represented in Figure 2a and in Figure 2b respectively (Arano et al 2023b).

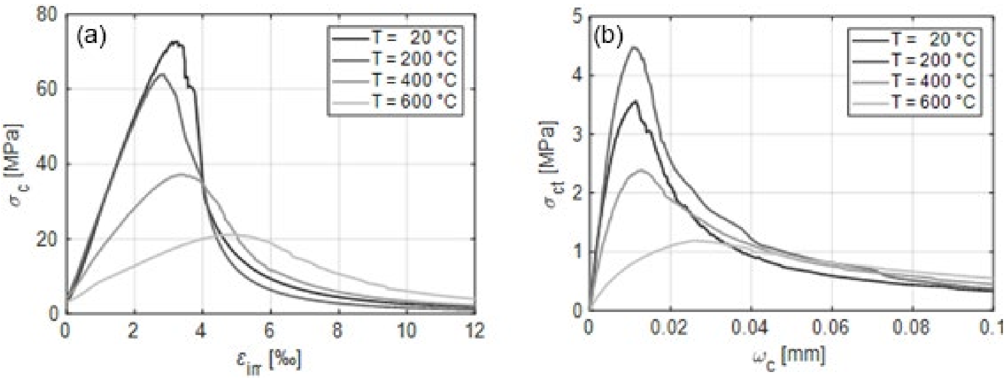


Figure 2: (a) Average compressive stress-strain curve (b) Average tensile stress-crack opening curve (Arano et al. 2023b)

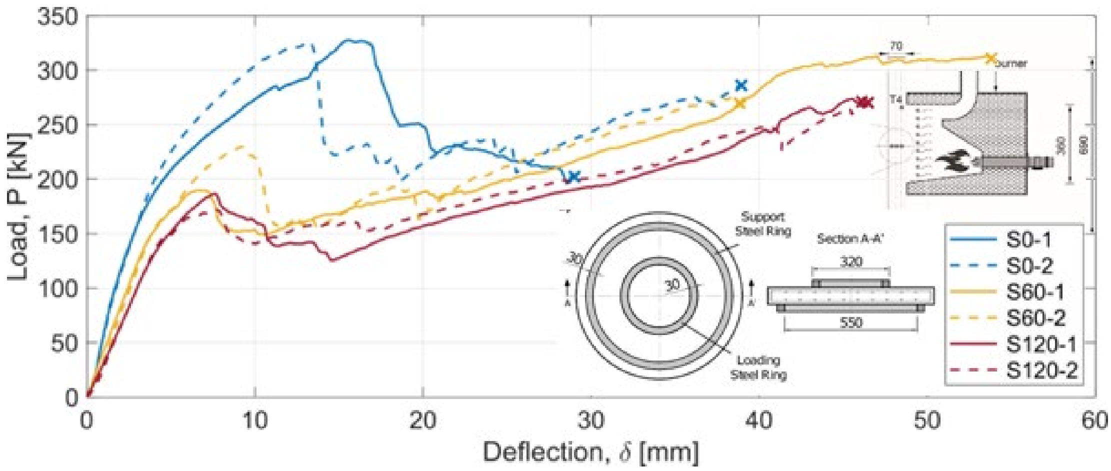


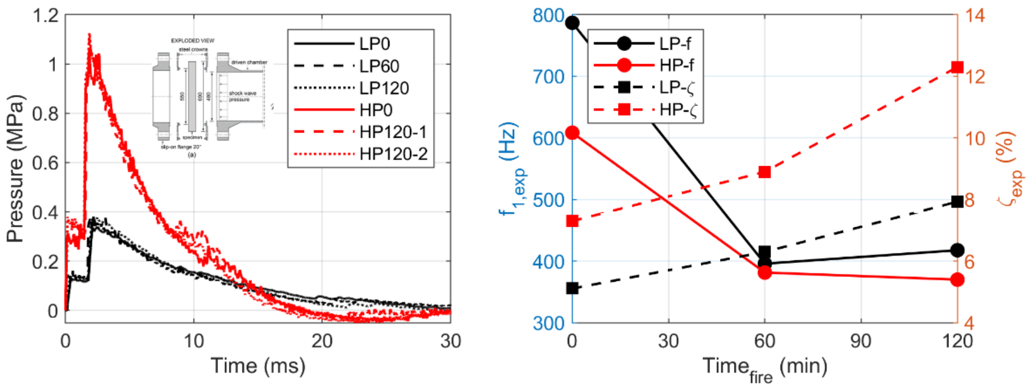
Figure 3: Experimental set-up and results of the static bending scheme on slabs (Reprinted with the permission of the publisher – Arano et al. 2023a).

4. Static behaviour of slabs in case of fire exposure

The effect of fire exposure on the static structural response of RC slabs was also investigated (Arano et al. 2023a). A hydrocarbon fire curve was applied to the slab by means of a gas burner, studying two fire exposure times (60 and 120 min) in addition to the reference (unexposed) case. The gas burner was placed in front of the sample (Figure 3a). A bending static test of each slab was then performed after fire according to the scheme represented in Figure 3b. Results of the load-deflection response are represented in Figure 3 in terms of load vs. central deflection.

5. Blast and fire interaction tests

The structural performance of RC slabs subjected to fire exposure and, subsequently, to a blast load was investigated (Colombo et al 2021). In this study, specimens identical to those tested under static conditions (RC circular slabs) were used. As for the static tests, a hydrocarbon fire curve was applied by means of a gas burner, considering the same two fire exposure times (60 and 120 min) in addition to the unexposed reference case. Dynamic tests were then carried out in residual conditions using a shock tube device (Colombo et al. 2011) with the slab in simply supported conditions. Two distinct pressure histories, referred to as LP and HP, respectively, with peak pressures of 0.35 MPa and 1.1 MPa, are depicted in Figure 4 for all the tests carried out. The acceleration of the specimen during the shock wave application was measured at the slab centre (A1). Results showed that thermal damage from the fire exposure causes a reduction of the overall stiffness of the RC slabs. As a consequence, the main frequency of the specimen is considerably reduced. Such damage in the specimen leads to a plastic state with irreversible deformations. As a result, higher energy is dissipated which leads to an increase of the damping ratio. The evolution of the first natural frequency and damping with fire exposure time and blast load is shown in Figure 4.



(a) (b)

Figure 4: Pressure–time histories applied to the samples in shock tube tests (a); Evolution of the first natural frequency and damping (b) (Colombo et al. 2021)

6. Conclusions

The study aimed to investigate the subsequential effect of fire exposure and blast loading on RC slabs by analysing the impact of elevated temperatures on the mechanical properties of concrete, along with carrying out static and dynamic tests on heated RC circular slabs. The obtained constitutive behaviour of concrete material, in compression and tension, at several elevated temperatures confirm the pronounced reduction of strength and modulus of elasticity reported in the literature and in some Standards. The structural mechanisms observed during the static tests of RC slabs occur also after fire exposure, although with some differences. The dynamic tests show a considerable reduction of the fundamental frequency of the RC slab after fire exposure. The softening of the material leads to a more distributed crack pattern, also enlarging the maximum amplitude of the acceleration response. Both the thermal damage and the microcracks lead to a higher dissipation of energy, (linearly) increasing the damping ratio with fire exposure. Safety considerations of concrete structures require evaluation of accidental load scenarios involving extreme load conditions. The findings of the present study are valuable in order to define a reliable benchmark for numerical models which, upon numerical upscaling, will be instrumental for the design of the SFTB under the exceptional case of fire exposure and blast loading.

Acknowledgements

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