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PROPOSAL OF A TEST SET UP FOR SIMULTANEOUS APPLICATION OF AXIAL RESTRAINT AND VERTICAL LOADS TO SLAB-LIKE SPECIMENS: SIZING PRINCIPLES AND APPLICATION

José Gomes [(1)], Miguel Azenha [(1)], José Granja [(1)], Rui Faria [(2)], Carlos Sousa [(2)], Behzad Zahabizadeh [(1)], Ali Edalat-Behbahani [(1)], Dirk Schlicke [(3)]

(1) University of Minho, School of Engineering, ISISE, Guimarães, Portugal
(2) Faculty of Engineering of the University of Porto, CONSTRUCT, Porto, Portugal
(3) Institute of Structural Concrete, Graz University of Technology, Graz, Austria

Abstract

Cracking control in reinforced concrete (RC) is a key factor to ensure proper service life behaviour. However, current design recommendations are unable to provide straightforward methodologies for crack width prediction in RC structures subjected to the combined effects of applied loads and restrained deformations, which is a common situation in civil engineering. This is motivated by the lack of knowledge about the complex interactions that take place between self-imposed deformations, viscoelasticity and the effects of applied loads in the process of crack development.
A major challenge in studying these combined effects is the validation of numerical simulations with real scale experimental data. For that purpose, an experimental system for testing real scale RC slabs subjected to the above-mentioned conditions was developed. This system is capable of inducing a prescribed axial restraint to the slab, in correspondence to a high restraint degree that induces cracking in view of expectable shrinkage. At the same time, the setup enables the application of vertical loads.
The experimental results obtained in this work allowed for the validation of the test setup, as well as the suitability of the slab geometry and reinforcement.

1. Introduction

Cracking in RC structures is an acceptable phenomenon when controlled, but it is one of the main factors that affect structural durability when crack width exceeds the recommended limits. The design of RC structures that meet safety, functionality and aesthetic requirements during their lifespan, without additional maintenance costs, depends also on adequate design practices that allow engineers to properly predict expectable crack widths.

Even though there is a wide body of design codes and recommendations providing practices for predicting the crack width due to applied loads or imposed deformations, they do not provide unambiguous rules for estimation of crack width under the combined effects of applied loads and restrained shrinkage. Different simplified approaches based on the application of CIRIA C660 [1], simplified combinations of the Eurocode framework, deformation-based methods [2] and explicit crack width calculations in composed bending with a percentage of the cracking axial force [3] may lead to differences in reinforcement for controlling crack width as large as 50% [4]. In view of such challenges, several authors have used the finite element method (FEM) to perform nonlinear numerical analyses in RC structures subjected to the combined effect of applied loads and restrained shrinkage, to quantify the stresses and forces which occur due to these effects [5-8]. These works, although very important to better understand the stress/crack development mechanism of such structures, are still lacking the experimental validation of long-term real scale tests.
This paper intends to show the development of an experimental system for testing real scale RC slabs under the above-mentioned effects. The paper starts by explaining the principles behind the design of the test specimens and the system requirements. After describing the test setup and procedures, the results of the preliminary test are discussed, and the suitability of the test setup and necessary improvements are addressed. This paper is a short version of the report of the research project IntegraCrete on the same matter [9].

2. Sizing and requirements

The main requirement of the developed testing system is the ability to provide an axial controlled restraint to a slab-type specimen, while simultaneously allowing it to be loaded with sustained bending/shear. It was intended to simulate a stretch of slab on a highly restrained condition, whilst monitoring the restraining forces, the in-plane and out-of-plane deformations and the reinforcement strain.
The design of the tested specimen corresponded to the simulation of a real-case one-way slab supported by transverse beams, under high axial restraint. Spans of 4.0m were considered for the slab, and a sizing considering permanent loads of 2kN/m^2 (acting together with the self-weight) and variable loads corresponding to class A of EN1991-1-1 [10] (2kN/m^2 plus 1.2kN/m^2 relative to movable partitions) was performed. The slab was designed for the ultimate and service limit states according to EN1992-1-1 [11], which resulted in a 0.10m thick slab, reinforced for bending with ϕ8//0.10 in the bottom face. This provides adequate behaviour without direct consideration of restraint, which was considered a design start point.
As the experimental setup was devised to test the slab under simply supported conditions, the 4.0m span was corrected to match the distance in between zero bending moments, which corresponds to approximately 3/5 of the span. Therefore, the test setup has a free span of 2.4m. The slab is supported by a perpendicular rod at each extremity (Fig. 1), and even though cracking is expected in such region due to stress concentration, the control region for restraint will be limited to 1.4m in the mid-span. The specimen is 0.50m wide, as to ensure a width-to-height ratio of 1/5, and therefore have a standard slab-type behaviour.

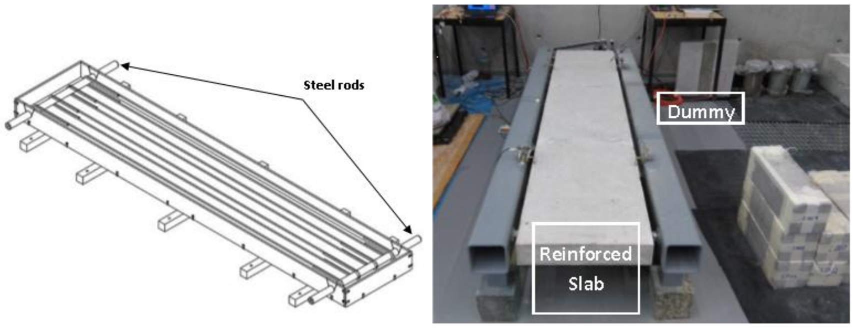

Figure.1 - Slab formwork and steel rods (left); Test setup (right).

3. Test set up and procedures

The long-term experiment that simultaneously combine the effect of self-induced deformations together with applied loads is conducted through the instrumentation of two specimens: a RC slab tested on the restraint frame and an unrestrained complementary plain concrete specimen (dummy) (Fig. 1). Furthermore, nine cubes (15cm edge) and three cylinders (15cm diameter; 30cm length) of the same batch were used for characterization of the concrete at different ages (compressive strength according to EN12390-3 [12] and E-modulus according to LNEC E397 [13]). The above-mentioned test setup, designed according to Section 2 to ensure the necessary performance requirements, is described next.

3.1 Geometry and materials

The slab, made of a C20/25 concrete strength-grade class, is 2.6m long and has a transversal cross-section of $0.5\times0.1m^2$. A free span of 2.4m is assured by two 40mm steel rods embedded in the slab at mid-height and connected to the restraint frame (see Fig 1).

Even though the design of the slab reinforcement that has been addressed in Section 2 foresees a solution of 8mm rebars spaced by 100mm, for this prototype slab both top and bottom flexural reinforcement are materialized with 8mm rebars transversely spaced by 125mm (larger than 100mm as initially planned due to a placement mistake, which was however considered acceptable for the sake of this prototype testing stage). A secondary transverse reinforcement of 6mm rebars spaced by 300mm was applied, to fulfil the rule of 20% of the principal reinforcement, as recommended by EN1992-1-1 [11]. The described reinforcement has a concrete cover of 22mm. The complementary specimen is made of plain concrete of the same batch of the slab, has the same cross section ($0.1\times0.5m^2$) and is 0.5m long. This specimen is not restrained, being simply placed vertically next to the restrained slab.

The slab was cast and tested in an experiment room without specific control of temperature or humidity. Recorded temperatures during test indicate variations between 20-28ºC. Environmental humidity ranged 50-70%. Concrete was kept from drying before demoulding of the slab and dummy (at 7 days) using a plastic foil. From 7 days onwards, the slab was subjected to drying at all surfaces.

3.2 Restraining device

The slab is simply supported and its axial deformation is restrained by controlling the axial force of the slab using hydraulic actuators, placed inside a metallic frame and connected to the steel rod embedded in the slab. This frame is constituted by two 2.65m long rectangular hollow section (RHS) steel profiles with outer dimensions of 140×140mm^2 and an inner hollow region of 124×124mm^2, supported by two 0.15m long RHS with outer dimensions of 80×80mm^2 and an inner hollow region of 72×72mm^2 (Fig. 2).

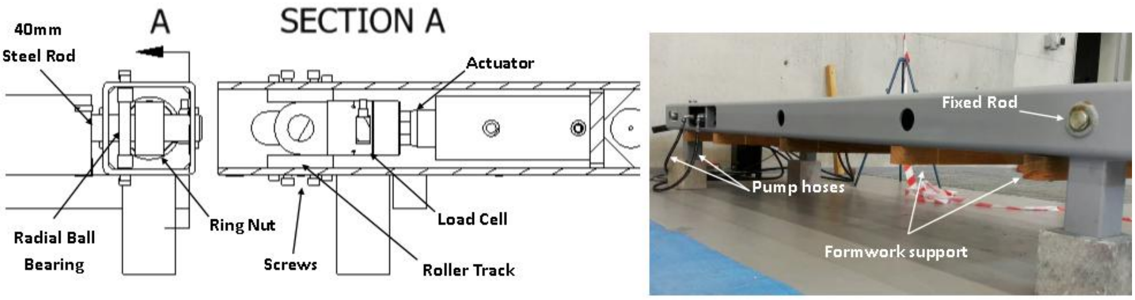

Figure 2 - Restraining device: inside the metallic frame (left) and overview (right).

Each longitudinal RHS has five drills on the bottom to enable the fixation of the formwork in the frame with wooden slats. On the lateral side there are two 40mm diameter holes to insert both fixed and moving steel rods. The positioning of the moving rod is done with a radial ball bearing between two roller tracks, whose position is adjusted with 4 socket head cap screws (Fig 2). For application of the axial load to the slab, two double effect hydraulic actuators supplied by a manual hydraulic pump are used, each with a 100kN capacity in compression and a 50kN capacity in traction, connected to the moving steel rod embedded in the slab.
Information about self-induced deformations of the slab are given by the dummy, and in both specimens the temperature and deformations are measured by means of electrical resistance stain gauges for rebar stress/strain assessment, a vibrating wire strain gauge (VWSG) acquiring the dummy deformation, linear variable displacement transformers (LVDT's) for slab deflection and longitudinal strains measurement and resistance temperature detectors (RDT's). The axial force applied by the actuators is measured by two load cells connected to the 40mm steel rod through a ring nut (Fig. 2).
On each side of the slab, one LVDT is fixed to a bracket, partially embedded in the concrete with a metallic clamp, and the concrete deformation in the central region of the slab is measured using a steel cable in tension, fixed between the other bracket and a steel plate in contact with the LVDT, as the steel plate is connected to the LVDT bracket with two springs (Fig. 3). With this spring system it was possible to measure the longitudinal strains of the slab during the application of the axial load.

4. Results

The test specimens were cast and left undisturbed for 7 days, with the actuators fully inactive (and free to move). At the age of 7 days (~174h), both the slab and dummy were demoulded and a tensile axial load of approximately 16kN was applied. The result of such load application in both load cells and longitudinal LVDTs is shown in Fig. 4. The longitudinal strain of 10-15με measured by the LVDTs was consistent with the corresponding calculated value, taking into consideration the geometry of the slab and the modulus of elasticity of the rebars and concrete [14] (200GPa and 26.3GPa, respectively): ~12 με, although a more precise concrete strain measuring device must be devised for next experiments in order to minimize the noise-to-signal ratio of the system.

At the age of 59 days the slab was loaded with 14 concrete blocks adequately spaced to avoid arch effects, and to simulate a quasi-permanent load combination (live load of 2.96kN/m^2). The blocks were placed sequentially from the mid-span towards the supports, leading to the formation of a single crack at mid-span, with a width of approximately 0.2mm, as shown in Fig. 4. As it was expected, the measured crack was wider than what is predicted from the EN1992-1-1 [11] formulation (~0.07mm), since the combined effect of restrained shrinkage and applied loads has to be taken into account.

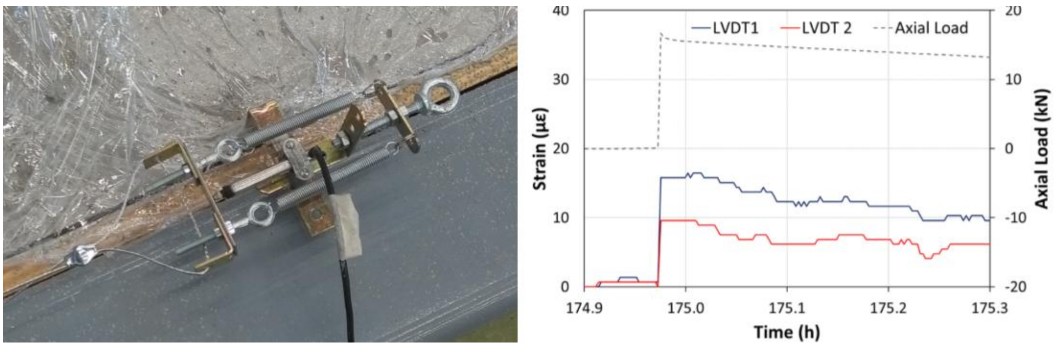

Figure 3 – Concrete strain measurement setup (left) and results after axial loading (right).

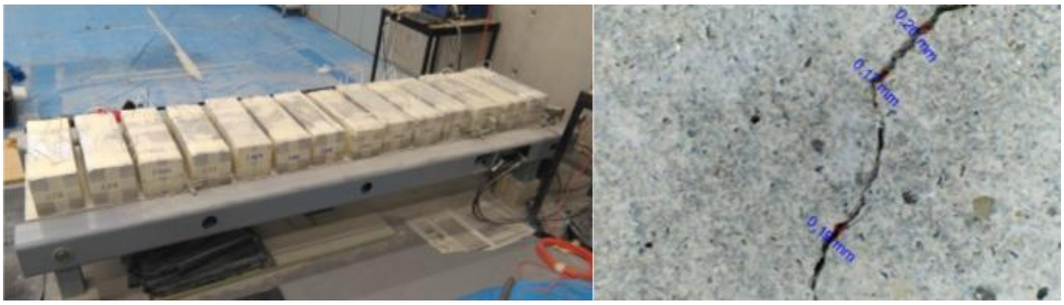
Figure 4 – Load blocks (left) and crack at midspan after application of the load blocks (right).

5. Conclusions

The current work describes the arrangement and preparation of the experimental setup designed for conducting long-term tests with real scale slabs subjected to the combined effect of applied loads and restrained shrinkage deformations.
The formwork support solution proved to be adequate, in the sense that it was possible to easily mount it and demould it in the restraining frame. The geometry of the specimens was accurate and therefore viable.
So far, the monitoring devices showed satisfying results at past key moments. Although there is some oscillation on the strain measurements, this was mostly caused by the fact that the experiment was not conducted in a controlled temperature chamber. This will be overcome in the next setup application. Even though the LVDT measurement system shown performed well, there are still operational drawbacks that can jeopardize reliability and thus deserve improvement in order to minimize the noise and the influence of the curvature of the slab in the measurement. The loading frame/setup has demonstrated capacity to impose and keep/control of the axial load, with an example application being demonstrated herein.

In general, it can be claimed that the trial experiment has shown to be successful and that relevant hints for improvement were obtained. The production of a second setup is envisaged for a wider program to be conducted on long term.

Acknowledgements
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