Full-Scale Tests of Steel Fibre Reinforced Concrete and Self-Stressing Steel Fibre Reinforced Concrete - Overview

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Abstract. Self-stressing steel fibre-reinforced concrete (SFRSSC) is increasingly utilised every day, with its areas of applicability expanding. One such application is ground-level elevated slabs on piles, along with elevated slabs on columns. Although regular steel fibre-reinforced concrete (SFRC) has been previously applied for such cases, albeit somewhat extensively, very few full-scale load-bearing tests have been conducted for these slabs under industrial-level loads up to failure. In Northern Europe, the use of SFRC in ground-level elevated slabs is somewhat common, either with or without additional traditional rebar reinforcement. On the other hand, SFRSSC is still an emerging technology with known benefits, and parts of the technology are yet to be discovered. No calculation method exists to validate the benefits of SFRSSC, specifically the self-stressing impact on load-bearing capacity at the ultimate limit state (ULS) and behaviour under serviceability limit state (SLS) loads. The aim of this presentation is to provide an overview of a comparative full-scale load-bearing capacity test up to failure, comparing two elevated slabs made of regular SFRC and SFRSSC loaded under similar conditions. Material properties were monitored by conducting an extensive battery of laboratory tests. The deformations, cracking, and shrinkage of the full-scale slabs were recorded using both standard sensors and innovative technologies, such as fibre optic sensors embedded in concrete and the digital image correlation method. The slabs were loaded with uniformly distributed sandbags up to the SLS load, and SLS criteria were measured. After unloading, the ULS load was applied; the slabs were evaluated and further loaded up to failure. The test results show that the slab made of SFRSSC had smaller deflections and crack widths, as well as a significantly higher load-bearing capacity.

Keywords: Steel fibre reinforced concrete, self-stressing steel fibre reinforced concrete, full-scale testing, fibre optic sensors.

1 Introduction

Steel fibre reinforced concrete (SFRC) gains more popularity in the construction industry with introduction of standards, e.g., SS812310:2014 [1] and more recently a new generation of Eurocode 2 which includes an informative Annex L on fibre reinforced concrete design [2]. Although there are quite a few guidelines and other publications on the design and capabilities of SFRC, there are a number of topics still disputed, *e.g.* safety of design methods, [3, 4] among others for achieving a safe yet economically viable solution via the usage of SFRC. A very common application of SFRC is a ground-level slab supported by piles, as described in ACI544.6R-15 [5]. Taking into account the sheer number of guidelines, reports and standards on the SFRC one may assume the strength and deformation properties of SFRC to be known and clear yet the discussions on those same topics render the area of research incomplete.

Steel fibre reinforced self-stressing concrete (SFRSSC) gains more visibility in the European, North American markets as well as others. By utilising a concrete self-stressing agent that expands the stiff concrete matrix along with randomly distributed steel fibres that are anchored in the concrete matrix, the technology creates a chemical self-stress in the structure by stretching the fibres in tension while placing concrete in permanent compression mimicking the post-tensioning of structures via steel cables.

The system is proving very feasible for ground level elevated slabs on piles [6, 7] among other structures [8]. The chemical self-stressing of the structure provides a stiffening effect on the structure, reducing the deflections as well as reducing the necessary amount of dilation joints and accompanying shrinkage cracks. Further research, nevertheless, is necessary to establish the system even further and answer more unknown questions. The aim of this study is to inform the public to the full-scale and lab-scale testing program conducted and shed some light on the differences of SFRC and SFRSSC structures at same conditions in terms of load bearing capacity, cracking, deflections among others.

2 Experimental Programme

The full-scale testing was simultaneously conducted for a regular SFRC slab and another SFRSSC slab, i.e. two slabs in total. The tested slabs were placed on a grid of columns where the tested, inner part of the grid consisted of d300 mm columns spaced at 3000 mm x 3000 mm distances. To simulate the behaviour of inner spans and to reduce the effect of outer edges, the slabs were designed with two additional spans around the loaded area. The slabs were placed directly on top of the columns as flat slabs without drop panels or “pile” heads without any connections between slabs and columns. The thickness of the slabs was 150 mm, which gives the span-to-depth ratio of 20 that corresponds to the common range used for ground level elevated slabs in industrial facilities.

2.1 SFRC and SFRSSC composite composition

The material composition used for the full-scale tests is presented in Table 1. Schwenk CEM II/A-LL 52.5N cement was used as binder. Sand 0/8 mm fraction from LVM quarry and crushed dolomite from Milsa quarry was used as fine and coarse aggregates, respectively. High range water reducing admixture (HRWRA) was used to maintain and adjust concrete workability and consistency. The water-to-cement ratio of both concrete mixes was set to 0.45 leading to an estimated concrete class of C30/37 and S4 slump. Hooked-end steel fibres of 60 mm length and 0.9 mm diameter and 1500 MPa tensile strength from Stalkanat Silur were used as the only reinforcement.

Table 1. Material composition for SFRC and SFRSSC.

Material	Amount, kg/m^3	
	SFRC	SFRSSC
CEM II/A-LL 52.5N	360	360
Water	162	162
w/c ratio	0.45	0.45
0-8 mm sand	952	952
5-16 mm crushed dolomite	914	914
HRWRA	3.6	3.6
Hooked end steel fibres (L=60 mm, d=0,9 mm)	50	50
Self-stressing agent	–	40

The concrete mix-designs are essentially the same apart from the addition of concrete self-stressing agent in case of the SFRSSC.

2.2 Loading

The full-scale load-governed testing includes loading the slabs to an apparent serviceablity and ultimate limit states, SLS and ULS, respectively, as well as loading up to failure. The assumed service load was set to be ~25kN/m^2 after adjusting the loading areas to the physical constraints of the loading material and method. The loading area has been selected following guidance from a recent and similar full-scale testing program, shown in Fig. 1. [9]

The loading pattern employs the maximum bending moments over the columns, negative bending moment, e.g. column on axis D/3, as well as the maximum positive bending moment, e.g. spans in axis C-D/3-5, with the least amount of loading material to cover both extremes as shown in Fig. 1.

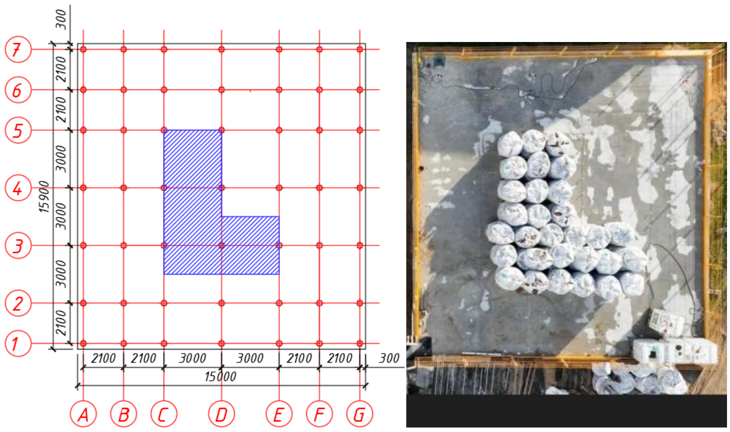

Fig. 1. Load layout: left - scheme, right – actual.

The slab was loaded by layers of sand bags, where each layer is regarded as load level (LL). The loading sequence is shown in Fig. 2 consisting of s main steps: loading to assumed SLS (LS3); load level kept at assumed SLS for 7 days (LS4); unloaded for 3 days (LS5), loading to assumed SLS (LS6) and kept overnight; loading to assumed ULS (LS7) and up to failure. There are several characteristic points marked in Fig. 2, which represent loading situations used for comparison of the two slabs. The loading levels have been chosen as assumed SLS=25 kN/m^2, assumed ULS=25 kN/m^2 x 1.5 = 37.5 kN/m^2. The multiplication between assumed SLS and assumed ULS was chosen following LVS EN1990:2023.

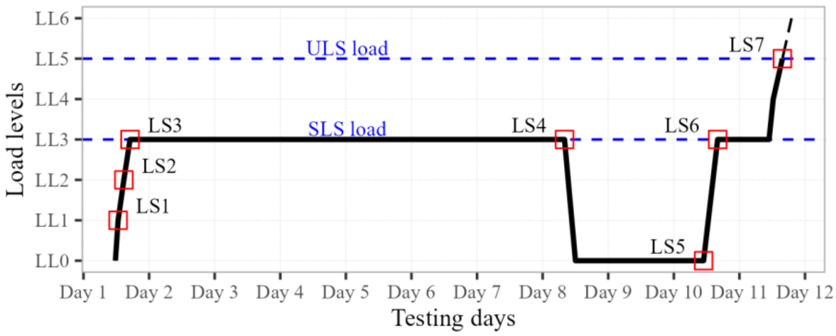

Fig. 2. Loading sequence with characteristic points denoted as loading situations (LS).

The loading material chosen was dry, sieved sand that was weighed and secured into big-bags of 1000kg or 10kN per single bag. This material was chosen due to its ability to alleviate any interlocking and arching problems that may occur with any kind of stiff materials, *p.e* bricks, concrete blocks *etc*. The material had insignificant absorption of water through the synthetic big-bags, thus the weights of the bags were very stable even in rain and slight ponding of water on the top surface of the slabs.

2.3 Instrumentation on site

To measure the structural response of the test slabs, a series of measurements were made continuously or at intervals. These include LVDTs for deflections, piezoelectric strain gauges, a mesh of fibre optic sensors, vibrating wire strain gauges (VWSG), digital image correlation (DIC), crack microscopes and crack opening gauges.
A row of LVDTs was mounted under the slab between axis C-D/3-5 to measure the deflections in the most loaded span of the structure. The LVDTs were mounted on a steel frame together with other equipment. To alleviate the influence on measurements from the base slab settlements under the loads from columns, the frame was lifted off the ground and secured to the columns.

The frame was also used for mounting cameras and lights for DIC measurements. This allowed for alternative method of capturing crack pattern on the bottom face of the slab. As can be seen in Figure 3 the bottom surface of the slab was first painted white and later on a dotted pattern was introduced for the cameras to have a distinct pixelation to follow the movements of the concrete. In total 6 cameras were being used to capture the behaviour of the slab, 4 cameras between axis C-D/3-5 and two between axis D-E/2-4 encompassing all of loaded spans and possible cracking in middle of spans.

The slabs employed a strain measurement system comprised of fibre optic cables in an unprecedented scale. Each test slab had a cast in-situ grid of cables in two layers encompassing the whole loaded area and more, placed in an orthogonal pattern in two layers, roughly 30 mm from faces of the slab. The grid used approximately 400 m of optical cables per slab with measurements being taken every 2,6 mm with 0,13 Hz frequency. Additionally, a pattern of fibre optic cables was embedded in the slab in the top surface of the slabs as well as a similar pattern in the bottom surface.

The chosen pattern of fibre optic cables gives a clear understanding of crack development areas and their directions. A “snake” pattern in bottom ensures capturing longitudinal and transverse cracking in middle of spans while the same pattern in top surface is placed directly above columns to capture cracking patterns above the column lines. Additionally, a set of 3 rings was placed above the most loaded columns to capture the expected fan pattern cracking.

To understand possible differences between measurement methods supposedly more suited for laboratory experiments, e.g. fibre optic cables, and on-site use, a set of multiple VWSGs were placed in the slab in the vicinity of the embedded optical cables. This allows for comparison and correlation of the two different strain measurement methods.

After initial cracking the crack openings were measured with a crack microscope and at certain locations crack opening gauges were glued on top of said cracks to evaluate their growth. The crack widths were measured with a microscope at column grid axes, and the results were compared to the ones obtained by DIC and fibre optic strain gauges.

Along the axis 3, linear piezoelectric strain gauges were glued on the top and bottom surfaces to ascertain the curvature of the slab and compare the results with the data obtained from the embedded fibre optic sensor.

2.4 Lab tests

In total, approximately 2,5 m^3 of concrete were used for laboratory samples for both fresh and hardened concrete properties. The properties determined were: shrinkage/expansion properties, post-cracking flexural strength using prisms and round slabs, fibre dosage, compressive strength at different ages using different shapes and forms of specimens. The samples taken ranged from cubes of 100x100x100 mm3 according to EN12390-2, 150x150x600 mm^3 beams according to EN14651 and EN12390-5, slabs d=800 mm h=100 mm according to ACI544.6R-15, slabs d=1500 mm h=180 mm according to ACI544.6R-15, up to samples of beams, cores, cylinders and slabs cut out and drilled from the tested structure itself.

The post-cracking behaviour of concrete was evaluated following up on research done previously for similar composition of SFRSSC [10, 11] via tests according to EN14651 and SIA162/6. The research previously utilised a limited scale of laboratory test samples to compare and evaluate the results coming from different test methods, i.e., simply supported structurally determinate beam with a notch and structurally indeterminate simply supported slabs, thus the current experiment may be seen as a full-scale real-life continuation of the previous research with an expansion into the full-scale testing realm.

3 Results and Discussion

The results of the two slabs show that SFRSSC slab at the same loading situations show smaller both crack widths and deformations (e.g. deflections) if compared to the slab made of regular SFRC (see Fig. 3). Also, the load bearing capacity of both slabs differ. The SFRC slab failed at the beginning of load level LL6 (5 layers and 9 bags), while the SFRSCC slab failed after LL7. The corresponding equivalent area loads were 45,7 kN/m^2 and 60,5 kN/m^2.

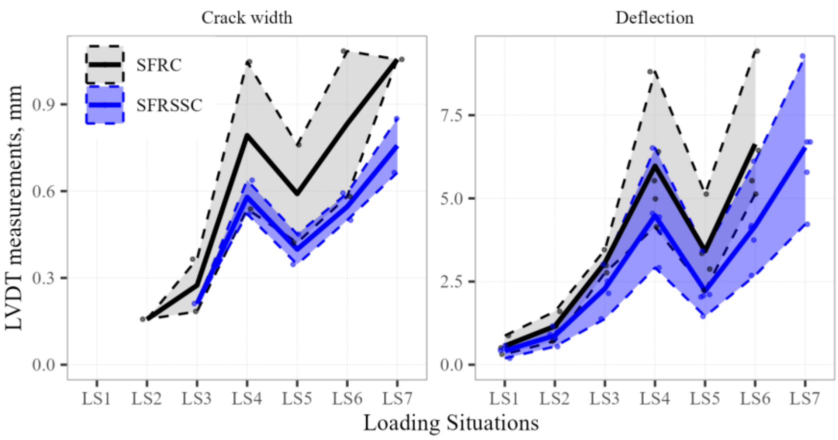

Fig. 3. Comparison of crack width and deflections measured by LVDTs for SFRC and SFRSSC slabs at different loading situations.

At the same load levels, the SFRSSC slab exhibited ~30 % less deflection (6,8 mm v 9,0 mm) than the SFRC slab. The deflections of the two slabs were clearly visible and growing with increased loading. Before the failure of both slabs the slab was clearly in a state of distress with visible top and bottom cracking along with noticeable deflections thus rendering the actual failure as ductile.

SFRSSC full-scale test slab exhibited crack openings on the bottom face of the slab by ~50 % less (0,6 mm v 1,1 mm). Additionally, a clear distinction of cracking pattern above the loaded column after removal of 7-day assumed SLS load was observed. The SFRC slab exhibited a clear fan pattern with crack openings up to 0,14 mm, while the SFRSSC slab exhibited 2 short cracks indistinguishable by the naked eye yet captured by the fibre optic sensors, measured with a microscope to be 0,04 mm wide.

Fig. 4 shows the different failure patterns of SFRC and SFRSSC.

Fig.4. Failure pattern for (left) – SFRC, (right) - SFRSSC.

The failure pattern of SFRC shows a clear yield line folded plate failure pattern while the SFRSSC slab, although exhibiting similar crack pattern, failed in a way more consistent with post-tensioned systems where the concrete is confined. In both cases the slabs showed visible cracking and deflections long before failure thus rendering both of the slabs ductile. The failure of both slabs happened in flexure.

Laboratory tests, VWSG, DIC, fibre optic and other measurements, although significant, are not looked at within this publication due to publishing constraints. Nevertheless, the results shall be published elsewhere in a more comprehensive manner and with more detail on the outcome of the full-scale tests.

4 Conclusions

The full-scale tests of SFRC and SFRSSC revealed the following conclusions:

- At failure the SFRSSC slab held ~25 % larger load than SFRC;
- At same loading intensity SFRSSC exhibited ~30 % less deflections;
- At same loading intensity SFRSSC exhibited ~50% less cracking on the bottom face and almost no cracking on the top surface;

• The seen results suggest that using SFRSSC allows for an increase of SLS and ULS loading when compared to SFRC *ceteris paribus*.

Further and deeper analysis of the data gained from the full-scale and lab-scale tests will be published at a later date.

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