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Two-way slabs: Experimental investigation of load redistributions in steel fibre reinforced concrete

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ABSTRACT

In the design of two-way reinforced concrete slabs, e.g. using the strip or yield line design method, the possibility of redistributing the load between different loading directions is used. The main aim of the present study was to investigate how fibres affect the structural behaviour such as the possibility for redistribution, crack patterns and load-carrying capacity. The investigation was conducted by means of experiments on two-way octagonal slabs, simply supported on four edges, centrically loaded with a point load. The slabs spanned 2.2 m in both directions and the reinforcement amount was twice as large in one direction as in the other, in order to provoke uneven load distribution. Three slabs of each reinforcement configuration were produced and tested: conventionally reinforced slabs, steel fibre reinforced slabs and a combination of both reinforcement types. The reaction force on each supported edge was measured on five rollers per edge. A moderate fibre content (35 kg/m^3) of double hook-end steel fibres was used. The steel fibres affected the structural behaviour significantly by providing post-cracking ductility and by increasing the ultimate load-carrying capacity by approximately 20%. Most significant, the steel fibres influenced the load redistribution in such a way that more load could be transferred to supports in the weaker direction after cracking. Further, more evenly distributed support reactions were obtained in the slabs containing both reinforcement types compared to the case when only conventional reinforcement was used. The slabs reinforced by steel fibres alone did not experience any bending hardening; however, a considerable post-cracking ductility was observed. Furthermore, the work presented in this paper will provide results suitable for use in benchmarking numerical and analytical modelling methods for steel fibre reinforced concrete, as the experimental programme also included extensive testing of material properties.

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1. Introduction

Although the use of steel fibre reinforced concrete (SFRC) has been increasing over the past two decades, the anticipated implementation of SFRC may have been hindered by a lack of guidelines and knowledge concerning the influence on structural behaviour, e.g. plastic redistribution. Extensive research has proved that steel fibres provide significant post-crack ductility to the otherwise brittle concrete. This effect has been quantified in numerous studies [1–3] and standards have been developed for assessing characteristic material parameters, e.g. fracture energy [4,5]. A common application of SFRC is in industrial flooring, i.e. slabs on ground [6,7]. More recently, SFRC has also been used as the only type of reinforcement in elevated slabs [8] or in combination with conventional reinforcement [9]. Documented benefits of SFRC include both the bending [6,10] and shear capacity [11] of slabs. In the design of two-way reinforced concrete slabs, e.g. using the strip or yield line design method, the possibility of redistributing the load between different load-carrying directions is commonly used.

Plastic redistribution fundamentally affects the structural design of concrete structures; a characteristic that incorporates the statical indeterminacy in the design of reinforced concrete, e.g. using the strip method [12] or yield line theory [13]. However, experiments designed to quantify the influence of steel fibres on the load redistribution, have to the knowledge of the authors not been performed before, although some effects have been observed [14].

In this study, the effects of steel fibres on bi-directional load redistribution have been quantified through experiments. In addition to the distribution between the two load-carrying directions,

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Nomenclature

$(1/r)_i$	curvature of cross-section in direction i
α	angle at which the reinforcement intersects the yield line
α	rotation angle of support roller
δ	virtual displacement by the point load P
δ_i	deflection corresponding to CMOD_i
δ_L	deflection at the limit of proportionality in three-point bending test
ϵ_c	concrete strain
ϵ_{cu}	ultimate compressive strain
ϵ_{fu}	ultimate tensile strain
ϵ_s	strain in reinforcement bar
λ	factor taking the non-linear distribution of compressive stresses into account
σ_s	stress in reinforcement bars
σ_{cc}	compression stress in concrete
θ	rotation angle in the yield lines
ϕ	reinforcement diameter
A_{si}	reinforcement area in direction i
CMOD_i	crack mouth opening displacement i
D_{BZi}	energy absorption capacity, corresponding to CMOD_i
E_c	elastic modulus of concrete
EW	external work on the slab
F_i	load in three-point bending test, corresponding to CMOD_i
F_L	load at the limit of proportionality in three-point bending test
L_S	half diagonal of a square slab (Fig. 2)
L_Y	length of a yield line
IW	internal work resisted by the reinforcement in the slab
P	point load
V_f	fibre content in percentage
b_{3PBT}	width of three-point bending specimen
d	diameter (of specimen)
d_i	internal lever arm of reinforcement in direction i
f_y	yield strength of reinforcement
$f_{c,mean}$	mean compressive strength of concrete
$f_{ct,mean}$	mean tensile strength of concrete
f_{Ftu}	reference value describing the residual strength in cross-sectional analysis
f_{Ri}	residual flexural strength, corresponding to CMOD_i
h	height (of specimen)
h_{sp}	notched height of three-point bending specimen
l_z	span length in three-point bending test
m_b	moment resisted by reinforcement
m_i	moment capacity of the reinforcement in direction i
s_i	spacing between reinforcement bars in direction i
t	thickness
x	height of the compressive zone

the load distribution over the length of the support was also measured. Furthermore, as the experimental programme also included extensive testing of material properties, the work presented in this paper will provide results suitable for use in benchmarking numerical and analytical modelling methods for steel fibre reinforced concrete.

To study redistribution, a structure that would to a high degree illustrate such an effect was chosen: a two-way slab unsymmetrically reinforced by conventional reinforcement. The geometry and test set-up were chosen in order to induce a flexural failure. To study redistribution, the distribution of reaction forces during loading was monitored. To facilitate this study, a support system using hollow steel rollers with strain gauges was developed. A finite element analysis was used prior to experiments to verify both the global structural behaviour and the local behaviour of the support rollers. The design of the test set-up is discussed further in Section 2.

2. Design of test set-up

2.1. Review of experimental work in the literature

Previous experimental work on the influence of steel fibres in reinforced concrete slabs has, as mentioned, resulted in benefits, e.g. increased punching shear resistance and increased flexural ductility. A number of studies have been conducted on the influence of steel fibre reinforcement on the punching behaviour of two-way slabs, concluding that steel fibres increase punching shear resistance [15,16,11]. Generally, slab-column specimens have been used.

Furthermore, an increase in both capacity and ductility of wall panels has been reported. Ganesan et al. [17] present a study on the effect of 0.5% steel fibres on the strength and behaviour of reinforced concrete wall panels simply supported on all four edges. The panels were subjected to a uniformly distributed normal load applied with a minor eccentricity to simulate a typical load-bearing wall. Wall panel sizes ranged from 480 × 320 mm up to 1200 × 800 mm (all with a thickness of 40 mm). Extensive information on similar test set-ups can be found in e.g. Doh [18], who tested similar wall panels using conventional concrete.

Barros and Figueiras [2] conducted experiments on one-way slab strips in bending. The main purpose of the experiments was to verify an analytical model developed for steel fibre reinforced cross-sections. The strips had the dimension of 1.8 × 0.5 × 0.075 m and were reinforced both with conventional reinforcement and varying content of steel fibres (0, 30, 45, and 60 kg/m^3). All slabs featuring steel fibre reinforcement showed some degree of bending hardening. Both ultimate capacity and ductility increased with higher fibre content.

Slabs of larger geometries have been tested in two-way bending in different test set-ups, with results depending on the amount of steel fibres added and the varying composition of conventional steel reinforcement. Døssland [8] presented tests performed on a full scale slab measuring 3 × 7 × 0.15 m. About 0.8% steel fibres were used together with a minimum of conventional reinforcement bars resulting in higher capacities than expected. In addition, a slab with steel fibres as only flexural reinforcement, measuring 3.0 × 3.4 × 0.15 m, was tested. The slabs were loaded with a centric point load up until right before the expected failure. Due to joint reinforcement to the supporting walls, all four edges were considered fixed. Døssland [8] concluded that for shorter spans, SFRC can be used as sole reinforcement type. In Michels et al. [10], experiments on octagonal slabs (span 1.9–2.34 m, thickness 200–400 mm) were presented. All the slabs were reinforced with steel fibres alone ($V_f = 1.3\%$ (100 kg/m^3), undulated fibres) and failed in bending. The failure can be described as ductile, but without any significant bending hardening. The slabs were tested by being supported on a column positioned at the centre as well as by eight hydraulic jacks symmetrically placed along the free edges. Along with other experiments, Blanco [19] tested steel fibre reinforced concrete slabs. These slabs were 3 m long and 200 mm thick and the width varied between 1.5, 2.0 and 3.0 m. Hooked

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