Engineering Structures 92 (2015) 1–14

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Testing and finite element analysis of reinforced concrete column footings failing by punching shear

Todor Vacev [a,*], Zoran Bonić [a,*], Verka Prolović [a], Nebojša Davidović [a], Dragan Lukić [b]

[a] Faculty of Civil Engineering and Architecture, University of Niš, Aleksandra Medvedeva 14, Niš, Serbia
[b] Faculty of Civil Engineering Subotica, University of Novi Sad, Kozaračka 2, Subotica, Serbia

ARTICLE INFO

Article history:
Received 22 June 2014
Revised 19 February 2015
Accepted 20 February 2015
Available online 17 March 2015

Keywords:
Reinforced concrete
Column footing
Punching
Test
FEA
ANSYS

ABSTRACT

Finite element analysis (FEA) and engineering software is increasingly used in modelling of different structures and in analyzing their behaviour. The subject of this paper was an analysis of behaviour of reinforced concrete column footing laid on deformable subgrade and loaded by concentrated load until failure. The modelling and 3D nonlinear analysis were implemented by applying finite element method (FEM) and using software package ANSYS 14.5. Field test data were used for calibration of the FE model and validation of the adopted parameters for all materials. The comparison of the field test results and FEA results showed good agreement, but also revealed some questions regarding FEA, and especially concrete crushing.

1. Introduction

Design of shallow foundations, especially column footings, in most cases involves calculations in which the footings are considered as stiff, and distribution of contact pressures is adopted as linear. In such calculations, the important part represents checking of punching of the column through the footing, in cases with, and without reinforcement that accepts shear in the column zone. Such control, as well as the punching control of reinforced concrete flat slabs, is mostly based on experimental research. Behaviour of column footings laid on deformable subgrade was, as a rule, investigated using laboratory tests, which caused difficulties in simulation of real conditions. Due to the complexity of the problem, both in mechanical and in organization aspects, such experiments on real footing structures were very rare hitherto. Finite element analysis (FEA) of 3D models using some of the available software packages represents a good way to overcome those problems. Besides the significant saving of time, material, and labour, this method enables unobstructed tracking of behaviour of all materials in the foundation structure under load (soil, concrete, and reinforcement). In this paper a FEA of an isolated reinforced concrete (RC) column footing on gravel ground is shown. FEA was done using ANSYS software, which allows successful simulation of behaving of materials such as concrete, steel, and soil.

2. Experimental analysis of the column footing

2.1. Aim of the experimental analysis

The aim of the experimental analysis was to determine behaviour of isolated RC column footings rested on subgrade soil and loaded by proposed external load until their failure. Thereat, it is important to determine the occurrence and mechanism of cracking and crushing development, and the way of stress distribution in reinforcement and in concrete of the footing. Also, it would be important to analyze influence of the factors like: concrete strength at compression, applied percentage of reinforcing, emplacement and diameter of the reinforcement, type and characteristics of the soil, unevenness of the contact pressures, etc. The key result of the performed parametric study should be determining of the factors whose influence in column footing calculation is dominant.

The experimental research was performed by the authors of this paper, and it was conducted from 2009 to 2014. The experimental analysis programme included construction of complete foundation structure in situ, consisting of prepared subgrade soil with

* Corresponding authors at: Faculty of Civil Engineering and Architecture, University of Niš, A. Medvedeva 14, 18000 Niš, Serbia. Tel.: +381 631045368 (T. Vacev), +381 631048217 (Z. Bonić).
E-mail addresses: ttomas@eunet.rs (T. Vacev), zokibon@yahoo.com (Z. Bonić).

http://dx.doi.org/10.1016/j.engstruct.2015.02.027
0141-0296/

prescribed geotechnical characteristics and test specimens – column footings with proposed dimensions and defined characteristics of the concrete and the reinforcement.

2.2. Experimental setup and material data

For the purpose of the experiment, a testing steel frame was made, and its role was to accept the reactive force of the hydraulic jack that was used to load the footing.

The test frame (Fig. 1) was laid down in the foundation pit measuring 4.0 × 5.0 m in layout, and 3.0 m in depth. The structure of the frame and its dimensions allow for unimpeded formation of sliding surfaces in the soil underneath the footing, in case sufficiently high failure load is reached. In this way, we made a step further in respect to the earlier laboratory experiments in the literature, because the footing testing is conducted within the completely realistic boundary conditions in terms of the soil. Simultaneously, comparison and verification of earlier tests in laboratories (from the literature) with the in situ tests is provided. The excavated material was replaced by river aggregate with controlled density and granulometric composition (Fig. 3a). The prepared mixture was laid in layers 30 cm thick, with compacting of every layer using vibrating plate (Fig. 3b). After compacting of every layer, the mixture density was checked using plate bearing test (Fig. 3c). The measured mean values of the modulus of compressibility (M_s) in the layers were in range of 43.3–66.7 MPa, thus corresponding to normal compaction of subsoil. The compaction of the subgrade soil was controlled before testing of each footing. It ranged between 39.5 MPa and 76.7 MPa, and the corresponding modulus of elasticity of the subgrade soil was calculated.

The tested footing (Fig. 2) was loaded at its column top by vertical axial load using the hydraulic jack (Figs. 4b and 5). The load was increased until the punching of column through the footing occurred. The dimensions of the specimens for the proposed testing programme were 85 × 85 cm in layout and correspond to the earlier experiments of Hegger et al. and Kinnunen et al. [1–4]. The footing depths were 12.5 cm to 25 cm and the diameters of applied steel reinforcing bars were Ø8 mm. The reinforcement ratio (ρ) for all the footings was approximately 0.4%. The properties of the used steel were determined on three samples. The obtained values were as follows: tensile strength f_{su} = 653 MPa, yield point f_{sy} = 570 MPa, and corresponding yield strain $\varepsilon \approx 2.7$ ‰.

Relevant characteristics of the footing that was tested and analyzed by FEA are given in Table 1. Concrete compressive strength was obtained at the time of testing using three cube specimens with edge length of 15 cm and one standard cylinder specimen, and all averaged values were converted to a standard cylinder.

2.3. Testing procedure

The experimental analysis was conducted by placing the footing on the soil surface and by loading it using vertical centric force, which was applied by a hydraulic jack having capacity of 1000 kN and monitored at every second (dynamometer HBM RTN, Fig. 5). The hydraulic jack and dynamometer were positioned between the steel crossbeam and the footing (Fig. 4b and 5). The load was applied in the load steps of approximately 20 kN, and kept constant at every load step until total consolidation of the subgrade soil for that load step. The consolidation was verified by observed stagnating of the vertical displacements of the footing.

Fig. 1. Test frame and the foundation pit.

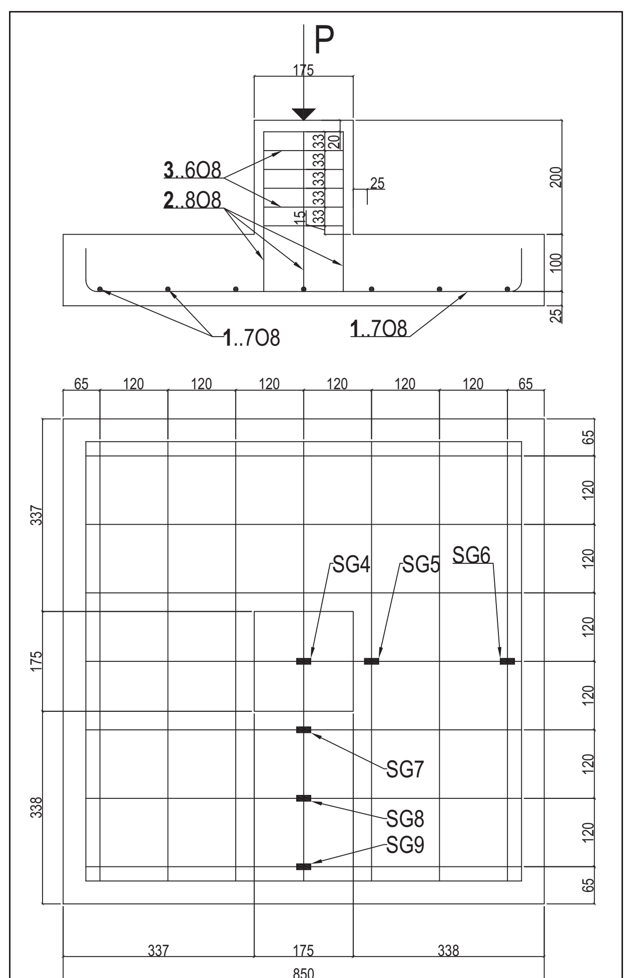

Fig. 2. Column footing (dimensions in mm); SG4...SG9 – strain gages for reinforcement strains.