Engineering Structures 56 (2013) 357–371

Contents lists available at SciVerse ScienceDirect

Engineering Structures

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

Post-tensioned girders with low amounts of shear reinforcement: Shear strength and influence of flanges

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ARTICLE INFO

Article history:
Received 21 February 2013
Revised 8 May 2013
Accepted 13 May 2013
Available online 15 June 2013

Keywords:
Shear design
Prestressed concrete
Post-tensioning
Experimental programme
Stress fields
Girder flanges

ABSTRACT

Assessing the strength of existing structures has become a major issue for structural engineers. Such analyses are often performed after changes of use of the structure or due to new design codes requirements. This is particularly relevant with respect to the shear strength of post-tensioned concrete bridges. Such structures were often designed in the past with fairly low amounts of shear reinforcement and do not comply with current code requirements in terms of amount of transverse reinforcement or shear strength. However, it should be noted that codes of practice cover the design of a wide range of cases and sometimes neglect some load-carrying actions or may be too conservative for assessing others. Therefore, the use of more refined models may potentially increase the predicted shear resistance and avoid unnecessary strengthening of existing structures. In this paper, an investigation on the behaviour of post-tensioned beams with low amounts of shear reinforcement and flanges is presented. First, the results of an experimental programme on twelve reinforced concrete beams (10.0 m long, 0.78 m high) failing in shear are described. The test series is used to analyse the most significant parameters influencing the shear strength and the failure modes. Its results are compared to a number of design codes showing different levels of accuracy. The test results are finally compared to the results of analyses based on elastic–plastic stress fields. This technique shows excellent results when compared to the test results and allows investigating on the role of the various shear-carrying actions, of the prestressing level and on the transverse reinforcement amount with respect to the various potential failure modes.

1. Introduction

Prestressing enables simple and economic construction of medium to large span concrete structures providing sufficient strength at ultimate and controlling the deflections and cracking state under serviceability conditions. Therefore, a large number of thin-webbed concrete girders have been built in the second part of the last century by using this technique. Design of these members has significantly evolved, from analyses of the stress state under service loads to equilibrium-based models at ultimate limit state. The evolution of design models as well as changes in actions and/or geometry (deck slab widening or others) require often the assessment of the performance of such existing bridges. This task frequently shows insufficient shear strength for existing members assessed with modern codes due to too low amounts of available shear reinforcement or insufficient stirrup anchorage and leads in many cases to expensive retrofitting of existing bridge girders. However, it should be noted that design codes are usually intended for design of a wide number of structures with a sufficient level of safety. For instance, for prestressed bridges, a number of shear carrying actions are usually neglected or estimated in a coarse (excessively safe) manner. This is the case of the shear force carried by flanges, the effective concrete strength at web crushing, the increase of the stress in the tendons, or the minimum allowable angle of the compression field in the web.

The behaviour of prestressed girders with varying amounts of shear reinforcement has previously been investigated by a number of researchers [1–10], mostly by testing simply supported members. However, the behaviour of prestressed continuous beams and the influence on their behaviour of flanges as well as detailing of the stirrups has been poorly addressed in the past. Nevertheless, these members are representative of continuous box-girder bridges, widely used in current practice particularly for long spans. In order to investigate more in detail the behaviour and strength of these members, a test series on twelve reinforced concrete beams was carried out at the Ecole Polytechnique Fédérale de Lausanne, Switzerland. The main parameters of the test series are the shear reinforcement ratio, the amount of post-tensioning force, the cross section shape and the stirrup anchorage detailing. The present paper describes the test series and its main results. The prediction of the behaviour of the test specimens has been done for a number of design codes as well as by using the elastic–plastic stress field

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http://dx.doi.org/10.1016/j.engstruct.2013.05.024

Nomenclature

A	cross section area of the beam in the testing region
E_c	Young's modulus for the concrete
E_s	Young's modulus for the rebar steel or the prestressing strand
P	nominal post-tensioning force
P_{test}	post-tensioning force at the testing day
Q	applied load at the cantilever
R	radius for the deviation of the prestressing tendon
V	shear force
V_P	shear force carried by the prestressing tendon
V_R	shear strength
$V_{R,test}$	resulting shear strength of the tests
$V_{R,model}$	resulting shear strength of a model analysis
$V_{res,test}$	residual shear strength (calculated at twice the deflection at peak shear strength)
V_{bot}	shear force carried by the bottom flange
V_{top}	shear force carried by the top flange
V_w	shear force carried by the web
d	effective depth to main tension reinforcement
d_g	maximum aggregate size of the concrete
f_c	concrete compressive strength (cylinder)
f_{cm}	average concrete compressive strength at the testing day (cylinder)
f_{ctm}	average concrete tensile strength at the testing day (direct tensile test)
f_y	yield strength of the rebar steel or the prestressing strand
f_t	ultimate tensile strength of the rebar steel or the prestressing strand
s	spacing of the rebars
t	crack opening
t_w	web thickness
$t_{w,eff}$	effective web thickness with reduction due to the prestressing tendon
v	deflection at the loading point in the span
w	opening of the crack normal to the crack surface
z	lever arm of the internal forces
Δ	sliding of the crack parallel to the crack surface
ΔV_P	increase in shear force carried by the prestressing tendon
Δt_w	increase in web thickness
$\Delta\varphi$	unintended deviations per unit length for the prestressing tendon
$\Delta\varepsilon_P$	increase in strain of the prestressing tendon
β_P	inclination of the prestressing tendon
ε_u	ultimate strain of the rebar steel or the prestressing strand
ε_x	strain in the horizontal direction (x)
ε_z	strain in the vertical direction (z)
ε_2	concrete compressive strain in the principal direction
η_{fc}	strength reduction factor to account for the brittleness of high strength concrete
η_ε	strength reduction factor to account for the tensile strains in transverse direction to the compression
θ_{crack}	measured angle of cracks in the testing region
θ_σ	inclination of the principal concrete compressive stress
θ_ε	inclination of the principal concrete compressive strain
μ	frictional coefficient for prestressing tendons in the steel duct
ρ_w	shear reinforcement ratio in the testing region
σ_c	concrete compressive stress in the principal direction
τ_{xy}	concrete shear stress in the direction of the girder axes
υ	direction of the crack opening with respect to the normal direction of the crack surface
Ø	diameter of the reinforcement bar or the prestressing strand
Avg	average
CoV	coefficient of variation
LoA	level of approximation

method (EPSF). This latter method was developed by Fernández Ruiz and Muttoni [11] and can be considered as an enhancement of the rigid-plastic stress fields (refer for instance to Muttoni et al. [12]). The EPSF method is solved by using the finite element method and allows accounting for compatibility conditions in a reinforced concrete element as well as for the role of transverse cracking on the concrete strength [13]. A comparison of the test results with the model prediction of the EPSF method is presented in this paper, showing an excellent agreement and allowing to investigate the role of the various shear carrying actions and failure modes.

2. Experimental programme

A test series on twelve reinforcement concrete beams was performed to investigate the behaviour of continuous bridge girders with low amounts of shear reinforcement (ρ_w defined as the ratio between the cross section of the transverse reinforcement and the corresponding web area), different ratios of post-tensioning (defined as the ratio between the post-tensioning force P and the concrete gross cross section A), and different cross sections (with and without flanges). The three main parameters refer to the testing region and their nominal values are listed in Table 1. The static system of the test setup corresponds to a single span beam with a cantilever and represents the situation of a continuous bridge girder near an inner support (refer to Fig. 1). The test specimens correspond thus to the girders of a multi-span bridge with a span length of about 40 m at a scale 3/8.

2.1. Specimens

All test specimens are 10 m long and 780 mm high and present in the central part a testing region with a length of about 4.80 m (refer to Fig. 2). Ten beams are casted as girders with two flanges (cross section according to the tests in [7]) and the remaining two without flanges (rectangular cross section). All flanged beams have a web thickness of 150 mm in the testing region and 400 mm in the external parts (to avoid shear failure), and a flange width of 800 mm. The web thickness of the two rectangular beams is also 150 mm in the testing zone and 300 mm outside.

The shear reinforcement ratio ρ_w varies between 0.063% and 0.251% for the different specimens and refer to the testing region in the centre of the beam. It can be noted that for $\rho_w = 0.063\%$ the reinforcement amount is lower than the minimum one prescribed usually in codes (in Model Code 2010 [14] for instance, $\rho_{w,\min} = 0.08 \cdot \sqrt{f_c}/f_y \approx 0.08\%$ for the investigated tests). Fig. 2b and c shows the reinforcement layout where the shear reinforcement in the central part is composed of stirrups with different anchorage conditions or links which are installed in alternating locations (opposite sides of the web). The longitudinal reinforcement consists of straight bars over the whole length of the girder. The design of the stirrups and links, their diameter and spacing,