Engineering Structures 101 (2015) 631–640

Contents lists available at ScienceDirect

Engineering Structures

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

Bearing stiffness in wood-to-wood compression joints

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ARTICLE INFO

Article history:
Received 22 April 2015
Revised 6 July 2015
Accepted 21 July 2015
Available online 13 August 2015

Keywords:
Post-tensioned timber connection
Connection stiffness
Compression tests
Spring model
Boussinesq's solution

ABSTRACT

In post-tensioned timber frames beams and columns are connected by means of a tendon. The tendon presses the beams against the columns which leads to a stress situation where beams are loaded parallel to the grain and columns are loaded perpendicular to the grain. These kind of wood to wood connections are semi-rigid and can therefore resist bending moments. An important factor influencing the behaviour of post-tensioned timber frames is the connection stiffness.

Compression tests perpendicular to the grain have been performed in order to estimate the perpendicular to the grain stiffness of a post-tensioned timber connection. The stiffness is represented by the modulus of subgrade reaction, which is the equivalent of a spring constant distributed over an area and which is a parameter frequently used in soil mechanics to calculate deformations and stresses under a foundation. The modulus of subgrade reaction is also needed to calculate the moment-rotation behaviour of post-tensioned timber connections.

The compression tests were evaluated using different analytical models based on spring models and the Boussinesq solution in order to estimate the perpendicular to the grain stiffness, i.e. the modulus of subgrade reaction.

The test evaluation showed that the modulus of subgrade reaction can be estimated based on the geometrical and mechanical properties of the column solely as suggested by the authors earlier if the Young's modulus is estimated according to EN 338. However, if the calculation is based on higher values from literature or tests, the stress distribution in the column has to be accounted for in order to get accurate results for the modulus of subgrade reaction.

The tests also showed that a reinforcement of the column is necessary in order to obtain a satisfactory stiffness in the post-tensioned timber connection. Reinforcing the Norway spruce (*picea abies*) column with European ash (*fraxinus excelsior*) increases the modulus of subgrade reaction significantly compared to a column made of spruce entirely.

1. Introduction

In order to compete with structures made of concrete or steel, timber structures have to be economical, quickly assembled and flexible in use. Post-tensioned timber frames can match these requirements. A respective system was first developed in New Zealand at the University of Canterbury [1]. The intent in the development of the system was to withstand strong earthquakes caused by the high seismicity in New Zealand, but the ongoing research also included systems for gravity loads [2–4]. Design proposals were published [5–8] and buildings using the post-tensioned timber frames were constructed [9], confirming the potential of the proposed system for multi-storey timber buildings.

A post-tensioned timber frame system has also been developed at ETH Zurich. The system differs from the one developed in New Zealand in the timber species used and in the reinforcement of the column. The ETH Zurich post-tensioned timber connection is built with glulam made from Norway spruce (*picea abies*). The column and the beams' bottom side are reinforced using European ash (*fraxinus excelsior*). The reinforcement is needed in areas where high stresses perpendicular to the grain occur as indicated in Fig. 1 (the grey shaded parts are made of ash). Moreover, using ash as reinforcement leads to a higher stiffness in the connection.

The tendon is placed in a cavity in the middle of the specimen and anchored at the end grain faces of the beams with steel plates. The steel plates transfer the force from the tendon to the specimen leading to a compression of the connection. No further steel

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http://dx.doi.org/10.1016/j.engstruct.2015.07.032
0141-0296/

Nomenclature

A	area	l_s	length of the beam block
B	control point	r	reaction force under the foundation
E_0	Young's modulus parallel to the grain	r_{edge}	reaction force at the edge of the foundation
E_{90}	Young's modulus perpendicular to the grain	t	thickness of the soil layer
$E_{c,90}$	Young's modulus perpendicular to the grain in compression	w	settlement in the column block or column, moisture content
F	force	w_{layer}	settlement in a soil-layer
W	constant in differential equation	x	coordinate in x-direction
W_1	constant in differential equation	y	coordinate in y-direction
W_2	constant in differential equation	Δ	stress distribution factor
b	effective width	β_1	angle in Boussinesq's solution
b_c	width of the column	β_2	angle in Boussinesq's solution
c	modulus of subgrade reaction	ν	Poisson's ratio
d_p	depth of the column block	ρ_w	density measured at a moisture content w
d_s	depth of the beam block	σ	applied stress
h_p	height of the column block	σ_m	stress at mid height of the column block
h_s	height of the beam block	σ_z	vertical stresses in the column block (Boussinesq)
l_p	length of the column block		

elements are required for the moment-resistant post-tensioned timber connection. The post-tensioned timber connection can be pre-fabricated and assembled easily on site.

An analytical model has been developed and a post-tensioned timber connection with ash reinforcement was subjected to experiments aiming at investigating the load bearing capacity and the stiffness of the connection as shown in Fig. 1 [10,11]. The developed model allows for good predictions of the moment-rotation behaviour of the connection area and for the estimation of the position of the neutral axis. In the model the tendon elongation is accounted for and the stresses are calculated based on linear-elastic analysis. The only input parameters needed are the modulus of subgrade reaction and the geometrical properties of the specimen. The modulus of subgrade reaction, a parameter frequently applied in soil mechanics, is the equivalent of a spring constant and is used in this study to describe the stiffness of the column. In [12] it was suggested to calculate the modulus of subgrade reaction only as a function of the Young's modulus perpendicular to the grain of the column and of its geometrical properties. This recommendation was given based on the assumption that the column was much less stiff than the beam, so that the latter can be modelled as a rigid body.

In those calculations, the Young's modulus perpendicular to the grain according to the European standard EN 338 [13] was used (860 MPa for deciduous solid timber of strength class D40), which is lower than values which are based on tests (approximately 1200 MPa [14]). The modulus of subgrade reaction was estimated 6.1 N/mm^3 leading to a slight underestimation of the initial stiffness in the moment-rotation behaviour that had been measured during the tests performed on a post-tensioned timber connection under gravity loads [12].

Since estimating the modulus of subgrade reaction based on experiments on a fully-sized post-tensioned timber connection is an elaborate procedure, compression tests on scaled specimens perpendicular to the grain have been performed. These tests were evaluated using different analytical models in order to estimate the modulus of subgrade reaction.

Two of the proposed models take into account the stress distribution within the specimen as recommended by Blass and Görlacher [15]. Another modelling approach can be found in [16], where an exact solution based on the equilibrium method of plasticity is presented. The model is able to reproduce the "slip lines" and therefore the stress spreading in the specimen. Moreover, this model is able to represent different load cases which could be verified by comparing the model with several test results [17].

It is the aim of the paper to calculate the modulus of subgrade reaction using geotechnical models, namely a coupled spring foundation and Boussinesq's solution for the stress distribution.

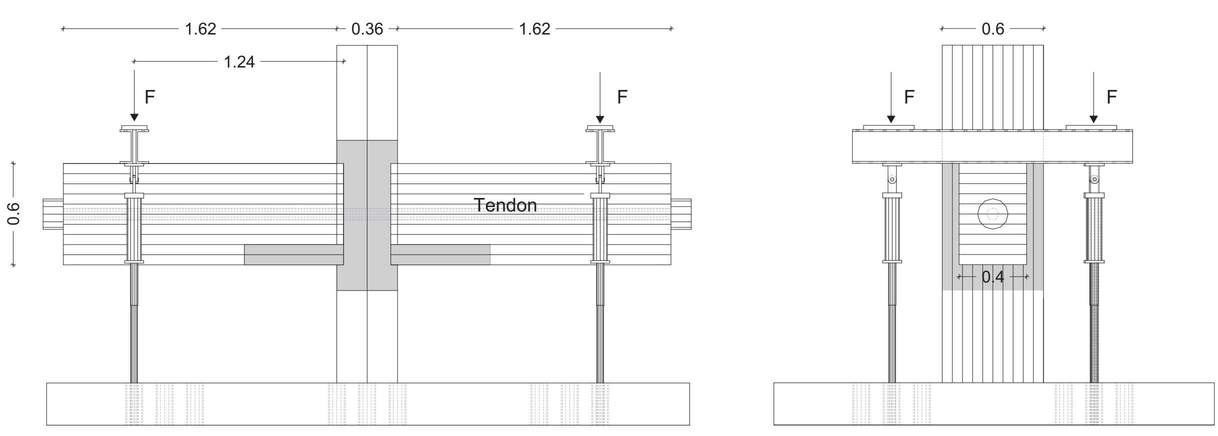

Fig. 1. Setup and dimensions in (m) for the tests performed on a post-tensioned timber connection under gravity loads F [12].