Engineering Structures 170 (2018) 91–102

Contents lists available at ScienceDirect

Engineering Structures

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

Influence of loading conditions on the shear capacity of post-tensioned beams with low shear reinforcement ratios

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A R T I C L E I N F O

Keywords:
Shear strength
Experiments
Digital image correlation
Loading conditions
Prestressed concrete
Post-tensioning
Moment–shear interaction
Continuous beams

A B S T R A C T

The majority of shear tests reported in the literature has been performed on simply supported reinforced concrete beams under point loads. In contrast, this paper focuses on the shear behaviour of post-tensioned T-beams with no or a minimum amount of transverse reinforcement under various loading conditions. Several test setups were used to investigate the influence of different distributions of the internal forces (due to uniformly distributed load and point loads, respectively) and of the shear slenderness on the shear resistance of the beams. Furthermore, the difference in the shear responses at the end support and the intermediate support of the beams was analysed using the experimental results. The experimental programme consisted of eight shear tests carried out on four specimens. With the aid of close-range photogrammetry, detailed measurements of the kinematics of the critical flexural shear cracks were taken. Linking well-known constitutive laws for concrete and steel with the relationship between the opening and sliding of critical cracks (determined using digital image correlation of experimental results) allowed the contributions of several shear transfer actions to the shear resistance to be estimated. In this paper, it is demonstrated that this approach leads to a better mechanical understanding of the actual shear behaviour of post-tensioned beams. The analysis illustrates that arching action plays a major role regarding the shear resistance of slender post-tensioned beams.

1. Introduction

Theoretical and experimental research on the shear strength of reinforced and prestressed concrete structural elements has a long tradition. Despite the huge amount of published shear tests in literature, there is still a lively discussion about which shear transfer actions (such as aggregate interlock, dowel action, transverse reinforcement, residual tensile strength, direct strut action, and vertical component of the prestressing force) govern at failure [1]. The complexity of this issue is related to the multitude of parameters involved, as stated by Leonhardt in the 1960s [2], and the fact that some of them also influence each other. Since many of the shear transfer actions depend on the shape and kinematics of the cracks and are thus related to stress transfer in cracked concrete, the formulation of a model with a clear physical background is very complex. This has led to the development of numerous analytical shear models for reinforced concrete (RC) and prestressed concrete (PC) structural elements, which assume that one or more of these shear transfer actions govern in order to determine the shear capacity of RC and/or PC beams with and without transverse reinforcement [3–13].

A closer examination of shear databases points out that the majority of the reported laboratory experiments were performed on small, single-span RC beams with rectangular cross section and no transverse reinforcement [14]. In most cases, a three- or four-point bending test setup was used in order to simplify the test procedure, resulting in a linearly increasing bending moment interacting with a constant shear force (see Fig. 1a). In practice, however, many concrete structures (for example bridges) have multi-span girders that are subjected predominantly to uniformly distributed loads. This results in large bending moments M combined with high shear forces V at the interior supports, and the internal forces decrease towards the point of contraflexure (see Fig. 1b). Therefore, in recent experiments, the effect of different M/V interactions and shear slenderness values on the shear resistance of continuous RC beams without transverse reinforcement subjected to uniformly distributed loads was investigated [15,16]. In these studies, it was shown that several shear transfer actions contribute to the shear resistance of beams without transverse reinforcement and that they are strongly influenced by the shape and kinematics of the cracks. The role of the M/V ratio as well as the difference between the effect of uniformly distributed and single point loads with respect to the shear

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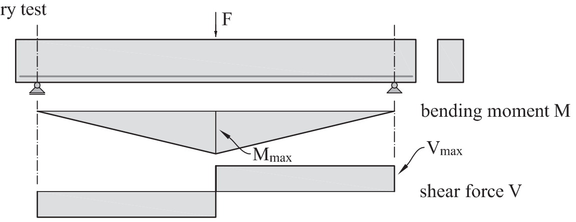
https://doi.org/10.1016/j.engstruct.2018.05.079
Received 21 February 2018; Received in revised form 15 May 2018; Accepted 18 May 2018

Nomenclature

A_c	cross-section area of the beam
A_{gt}	elongation without necking
A_p	cross-section area of the prestressing tendon
C_f	effectivity factor of the aggregate
E_c	Young's modulus of concrete
F	point load
F_{cc}	horizontal force resultant in the compression zone
F_q	equivalent point load in the interior span representing the uniformly distributed loads
G_F	fracture energy
M	bending moment
P_0	initial prestressing force at mid-section of the testing region
P_{test}	prestressing force at mid-section of the testing region minus all time-dependent prestressing losses
R_s	roughness index
V	shear force
V_{ag}	contribution of aggregate interlock to the shear capacity
V_{cc}	contribution of arching action to the shear capacity
V_{cr}	contribution of residual tensile stresses in the fracture process zone to the shear capacity
V_{da}	contribution of dowel action to the shear capacity
V_{lp}	shear force immediately before failure (when the last picture is taken by the DIC system)
V_{p0}	vertical component of the initial prestressing force
V_{sw}	contribution of the transverse reinforcement to the shear capacity
Z	ratio of point load to uniformly distributed load
a	shear span (distance between support and point load)
b	width of the member
c	height of the compression zone
f_c	mean concrete cylinder compressive strength
$f_{c,cube}$	mean concrete cube compressive strength
$f_{ct,sp}$	mean splitting tensile strength
f_t	tensile strength of reinforcement or prestressing strand
$f_{y,0.1}$	offset yield point at 0.1% strain
$f_{y,0.2}$	offset yield point at 0.2% strain
f_{yw}	yield strength of the stirrups
h	height of the structural member
k	unintentional angular displacement
l	length of the interior span or the beam
q	uniformly distributed load
s	crack sliding
w	crack width
w_{cr}	maximum crack width for stress transfer due to residual tensile stresses to occur
t_{pre}	age of concrete at time of prestressing
t_{test}	age of concrete at time of testing
ΔV_p	vertical component of the additional tensile force in the tendon caused by external loads
ΔV_q	shear force due to the uniformly distributed loads which is directly transferred to the support
$\Delta\varepsilon_c$	measured strain change on the concrete surface at the level of the tendon
$\Delta\varepsilon_p$	strain change in the tendon
ΣV_i	sum of the contributions of different shear transfer actions
α_p	angle of the tendon
δ	vertical displacement
ε_{cu}	ultimate concrete compressive strain
ε_t	tensile strain of the reinforcement
ε_2	principle compressive strain of concrete
μ	friction coefficient between strand and duct
ρ_w	shear reinforcement ratio
$\rho_{w,min}$	minimum shear reinforcement ratio according to codes
σ_{ag}	normal stress due to aggregate interlock
σ_{cp}	normal stress in concrete due to the horizontal component of prestressing force
τ_{ag}	shear stress due to aggregate interlock
τ_{b1}	bond stress before yielding of the stirrups
τ_{b2}	bond stress after yielding of the stirrups
φ_2	direction of the principle compressive strain of concrete
$\varnothing$	diameter of reinforcing bars or equivalent diameter of strands
$\varnothing_w$	diameter of stirrups
CEM	cement
COV	coefficient of variation
DIC	digital image correlation
RC	reinforced concrete
PC	prestressed concrete
$_m$	mean
$_{max}$	maximum

(a) Laboratory test



(b) Real structure

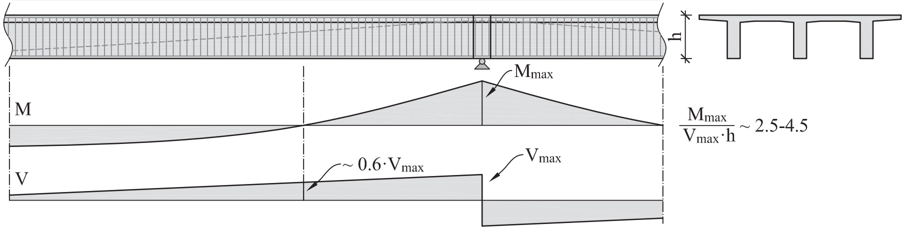


Fig. 1. Internal forces occurring in (a) a typical laboratory test on a single-span beam under point load, and (b) an interior span of a beam in a real continuous structure, such as a bridge, under predominantly uniformly distributed load.