Engineering Structures 111 (2016) 370–382

Contents lists available at ScienceDirect

Engineering Structures

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

Effect of support condition and load arrangement on the shear response of reinforced concrete beams without transverse reinforcement

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ARTICLE INFO

Article history:
Received 23 July 2015
Revised 13 December 2015
Accepted 16 December 2015
Available online 7 January 2016

Keywords:
Shear response
Simply supported beams
Cantilevers
Continuous beams
Load arrangement

ABSTRACT

This paper presents an experimental program on fourteen rectangular beams without transverse reinforcement differed by three support conditions, i.e. simply supported, cantilever and continuous beams, and two load configurations, i.e. one-point and uniformly distributed load. With the chosen test set-up, almost all *M*/*V*-combinations commonly encountered in practice can be investigated. The test results indicate significant differences of the shear response of members having the same cross-sectional properties but diverse *M*/*V*-combinations resulting from different support conditions and load arrangements. The shear resistance of the simply supported beam subjected to a uniformly distributed load is higher than that of similar beams subjected to a one-point load; the shear resistance of the cantilevers subjected to a uniformly distributed load is higher than that of simply supported beams; the shear resistance for cantilevers subjected to a uniformly distributed load with a longer cantilever arm is higher than for the shorter cantilevers having the same cross-sectional parameters. Furthermore, the slenderness and the flexural crack pattern have been found to decisively affect the critical shear crack formation, hence the shear resistance of continuous beams. The observed response is discussed and explained using a new approach recently developed by the authors. Comparison to the shear resistances predicted by formulas included in some codes of practice is also provided.

1. Introduction

In the principle of structural analysis, shear force in a flexural member is the result of the change of the bending moment over a certain length along the member axis. Thus, the co-existing bending moment can in its turn, affect the shear response of the member. This fact has already been considered in formulations included in some design codes of practice (CSA A.23.3-04 [1], AASHTO LRFD [2] and SIA 262 [3]) as well as in *fib* MC 2010 [4] that based on the two widely-recognized theories, i.e. the modified compression-field theory (MCFT) [5,6] and the critical shear crack theory (CSCT) [7,8]. In these formulations, the bending moment has a negative influence on the shear resistance. Having taken into account the effect of the bending moment, the physics and mechanics based theories predict the shear resistance of the simply supported beams not only under concentrated loads, but also under distributed loads better than empirical equations included in some most frequently used design codes, i.e. ACI 318-08 [9] and EC 2 [10]. Considering the fact that the shear resistance of a simply supported beam subjected to a distributed load, which is the most commonly encountered action type in practice, is considerably higher than that of the same beam subjected to a one- or two-point load, the application of these theories in the shear design of these structural members is advantageous [11]. By contrast, the predicted shear resistance according to these theories is then lower for members with predominant flexural action, such as cantilevers subjected to distributed load or frame corners and regions at intermediate support of continuous beams, than for members with less flexural action, such as simply supported beams. As a consequence, existing structural members, such as retaining walls, which have formerly been designed by empirical formulas and did not require shear reinforcement, may exhibit a deficit in shear resistance when recalculated with the formulations derived from the above mentioned theories.

The effect of the bending moment on the shear response has also been considered in the approach proposed by Tung and Tue [11]. Contrary to the formulations included in CSA A.23-04 [1] and SIA 262 [3], the flexural action is considered in the proposed approach to favor the shear resistance of a cross-section in the manner that with the same shear force, a higher flexural action would obstruct the critical shear crack formation. This could be justified through observing the crack pattern after shear failure in simply supported beams subjected to a one- or two-point load

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http://dx.doi.org/10.1016/j.engstruct.2015.12.022
0141-0296/

Notations

a	shear span	x_0	length of the uncracked region
b_w	web width	x'	distance from the peak of the concrete tensile stress to the neutral axis
d	effective depth of member	x''	height of the region with residual concrete tensile stress
$d_{b,crit}$	width of the critical shear band	z	effective shear depth acc. to *fib* MC 2010, can be taken as 0.9d
d_g	size of the maximum aggregate particles	ε_{ct}	strain of concrete by reaching the tensile strength
f_c	compressive strength of concrete	ε_s	strain in longitudinal reinforcing bar
f_{ct}	tensile strength of concrete	ε_x	longitudinal strain at the mid-depth of the effective shear depth acc. to *fib* MC 2010
k_{dg}	factor representing the size of the maximum aggregate particles acc. to *fib* MC 2010	ρ_s	reinforcement ratio for the flexural reinforcement
M	bending moment	τ_u	allowable shear stress in the critical width of the shear band
M_{cr}	crack moment of the cross-section	τ_{Rc}	relative shear strength, $\tau_{Rc} = V_{Rc}/(b_w d)$
n	modular ratio for reinforcement steel	σ_{xm}	average normal stress of concrete within the critical width of the shear band
s_{rm}	crack spacing of primary cracks		
V	shear force		
V_{Rc}	shear resistance provided by concrete		
x	cracked concrete section neutral axis depth		

where the critical shear crack normally appears in the low bending moment region. Furthermore, the flexural crack pattern can also affect the critical shear crack formation and hence the shear resistance, as the shear crack is considered to initiate from a flexural crack. From the basis of this approach, possible differences in the shear response between different primary types of shear span, i.e. shear span with constant shear force (type 1, e.g. simply supported beams or cantilevers subjected to a one- or two-point load), shear span with inverse changes of shear force and bending moment (type 2, e.g. simply supported beams subjected to distributed load), and shear span with coincident changes of shear force and bending moment (type 3, e.g. cantilevers subjected to distributed load), should be distinguished. As the bending moment is considered to favor the shear resistance of a cracked section in the proposed approach, the predicted shear resistance of a member of type 3 is generally higher than that of a member of types 1 or 2 having the same cross-sectional parameters. This contradicts the predictions provided by the above-referred theories and should experimentally be validated.

Over the last 60 years, numerous experimental investigations on the shear response of reinforced concrete members without transverse reinforcement have been performed. Significant experimental results can be found in the review performed by Collins et al. [12] or in the works of Reineck et al. [13,14]. Despite the large scale of the test data, most specimens are of the shear span type 1 in the form of simply supported beams subjected to a one- or two-point load. The test data of shear span type 2, simply supported beam subjected to a distributed load, are relatively limited, while only eight specimens of the shear span type 3 carried out by Pérez et al. [15] in the form of cantilevers subjected to a distributed load could be found in the preparing phase of this study. Since the test program of Pérez et al. [15] focused on the influence of the load configurations (uniform and triangular loads) and variable depth on the shear resistance, all load configurations have the same distance from the resultant load to the support of 2.75d. In the case of relatively short cantilever arms, the potential effect of the bending moment on the shear response, if it exists, might not be adequately distinguished and other actions such as direct strut action might rather be expected to take place.

This paper presents an experimental program on the shear response of beams with different combinations between moment and shear force diagrams (M/V-combinations). The program consists of two series; the first series mainly focuses on the primary shear span types, while the second one extends to the behavior of combined shear span types in continuous beams. Although the first test series has been introduced in [16] and the observed shear force at failure has been used for the validation of the proposed method [11], this series is shortly re-presented together with the newly performed second series in this paper so that the effect of support condition and load arrangement could be systematically documented and discussed. Comparison between the observed shear response and predictions is extended to the location of the shear failure and shear resistance for the both series, providing better understanding of the shear behavior of different structural members.

2. Effect of the bending moment on the shear resistance

To investigate the influence of the bending moment on the shear resistance considered in existing theories, the strength analysis for beams with different support conditions and load arrangements is performed, for instance, using the equations included in *fib* MC 2010 [4]. Considering the shear-carrying mechanism provided by the aggregate interlock as basic, the shear resistance of a member without transverse reinforcement according to the cross-sectional design procedure included in *fib* MC 2010 and some other design codes [1,2] is determined as

$$\upsilon_{MC} = \frac{V_{MC}}{d \cdot b_w} = \frac{0.4}{1 + 1500\varepsilon_x} \cdot \frac{1300}{1000 + k_{dg} \cdot z} \cdot 0.9\sqrt{f_{ck}} \quad (1)$$

where the longitudinal strain at the mid-depth of the effective shear depth at the control section can be calculated in absence of an axial force as

$$\varepsilon_x = \frac{1}{2E_s \cdot A_s} \cdot \left[\frac{M}{z} + V\right] \quad (2)$$

This formulation indicates the influence of both the bending moment and shear force on the shear resistance of a cross-section in the manner that the shear resistance becomes smaller when the bending moment and shear force become greater. Although the shear resistance according to Eq. (1) is in general determined at control sections, in the following the shear resistance at all other sections are also calculated using this equation for the analysis of the whole shear span.