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Quantification of shear cracking in reinforced concrete beams

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ABSTRACT

This paper presents an experimental work and analysis of test results on diagonal cracking behavior of reinforced concrete (RC) beams that failed in shear. The strain distributions of transverse reinforcement, obtained by closely spaced strain gauges mounted inside transverse reinforcement without disturbing bond, are presented in a form of contour lines at different load levels. The diagonal crack width, average principal and shear strain fields of the shear span were obtained by using the digital image correlation (DIC). Based on the strains of transverse reinforcement along the path of the critical diagonal crack, the shear strength contribution of the transverse reinforcement (V_s) is isolated from the shear strength contribution of concrete (V_c). The value of V_s calculated in this way is generally larger than that obtained from the strains measured at mid-height of stirrups in the case of strong bond, while the difference is insignificant in the case of weak bond. With the full and detailed pictures of internal and external strain fields of the beams, important shear characteristics such as inclination of the principal compression strain and its correlation with principal compression stress, variation of V_c and V_s with respect to crack width and member deflection, relationships between crack width, shear force, principal tensile strain of concrete, and strain of transverse reinforcement, etc. are studied in this work. These relationships shed light on further study of the shear behavior of RC beams.

1. Introduction

Failure of deep reinforced concrete (RC) beams in two Air Force warehouses in 1955 attracted the attention of researchers, resulting in reconsideration of the fundamental philosophy of shear design [1]. Since then, intensive experimental investigations have been conducted and significant advancements have been made in understanding the shear transfer mechanisms of RC members. Taking different mechanisms as main shear transfer actions, different design guidelines have been proposed [2–4]. A detailed review of how these transfer actions work to resist shear force is available in ACI-ASCE Committee 326 [1], ACI-ASCE Committee 455 [5], ASCE-ACI Committee 426 [6] and Collins et al. [7]. However, till now, the problem of shear and diagonal failure of RC members has not been resolved fundamentally and conclusively.

In most of the current design codes [2–3,8] and the old version of Eurocode 2 [4], a superposition methodology has been adopted, i.e. the shear resistance of a RC member (V) consists of the contributions of (i) transverse reinforcement (V_s) and (ii) concrete (V_c). Shown in Fig. 1 are the components of shear strength contributions around the critical diagonal crack (CDC). The equilibrium of the free body in the vertical direction results in:

$$V = V_c + V_s = V_c + \sum_{1}^{n} V_{si} \quad (1)$$

where V_{si} is the tensile force in the i-th shear reinforcing bar, and n is the total number of shear bars intersecting the CDC. V_{si} can be obtained by measuring the strain of the transverse reinforcement exactly at the location of the CDC. In Fig. 1, V_{cc}, $S\sin\theta_{cr}$ and V_{cd} are shear strength components from the concrete in uncracked compression-zone, aggregate interlock and dowel action of longitudinal reinforcement, respectively. θ_{cr} is the angle of inclination of CDC with respect to longitudinal axis of beam.

Two methods have been widely used in the literature for measurement of strains in transverse reinforcement: 1) installing strain gauges on the surface of stirrups at the mid-height [9–12]; and 2) attaching strain gauges on the surface of stirrups along an assumed diagonal crack path [13–17]. However, these methods cannot obtain accurate strain values due to two reasons: 1) the bond between steel bar and concrete significantly affects the strain distribution [18] and attaching strain gauges directly on rebar surface distorts the bond [19–20]; and 2) the path of the CDC is not known a priori.

The above problems can be resolved by measuring the strains along the full length of all transverse reinforcement bars in the

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Nomenclature

a	length of shear span
A_s	area of longitudinal reinforcement
b	width of beam
d	effective depth of beam
E_c	modulus of elasticity of concrete
E_s	modulus of elasticity of reinforcing steel
f_c'	concrete cylinder compressive strength
f_{yt}	yield strength of transverse reinforcement
M_u	bending moment at critical section
n	total number of transverse bars crossing CDC
n'	E_s/E_c
s	spacing of transverse reinforcement
s_c	crack spacing
$S\sin\theta_{cr}$	vertical component of shear transferred by aggregate interlock
V	applied shear force
V_c	shear resistance from concrete
V_{cc}	shear transmitted across the intact compression-zone concrete
V_{cd}	dowel force of longitudinal reinforcement
V_{cr}	shear force at first diagonal cracking
V_f	shear force at collapse of member
V_m	maximum shear resistance
V_s	shear resistance from transverse reinforcement
Vsi	tensile force in i-th shear reinforcing bar
V_u	shear force at critical section
w	measured crack width
$w_{cr,\ avg}$	average crack width
ρ_l	longitudinal reinforcement ratio
ρ_t	transverse reinforcement ratio
ε_1	principal tensile strain in concrete
ε_2	principal compressive strain in concrete
ε_c'	strain at onset of peak stress f_c'
$\varepsilon_{t,\ avg}$	average tensile strain in concrete
ε_x	concrete strain in horizontal direction
ε_y	concrete strain in vertical direction
θ	angle of inclination of principal strain to longitudinal axis of member
θ_c	angle of inclination of principal stress to longitudinal axis of member
θ_{cr}	angle of inclination of CDC with respect to longitudinal axis of member
CDC	critical diagonal crack
DIC	digital image correlation
DSFM	disturbed stress field model
LVDT	linear variable differential transformer
MCFT	modified compression field theory
RC	reinforced concrete
SG	strain gauge

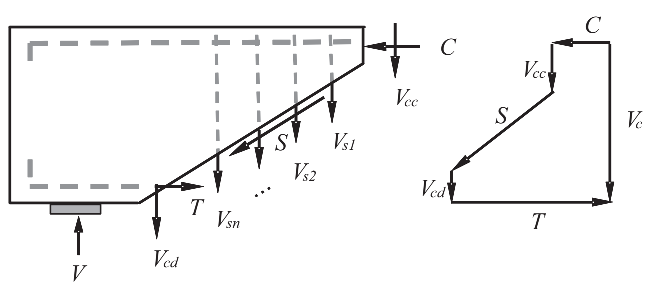

Fig. 1. Components of shear resistance.

whole shear span without disturbing the bond. A method for measuring the strain of every transverse bar at any location during a beam test is developed by the present authors (Fig. 2). The value of V_{si} is then calculated from the strain of a transverse bar at the exact position of CDC which is observed in the beam test. To avoid disturbance of bond, strain gauges are installed in the cavity in the center of a transverse bar. The design of the transverse reinforcement and strain measurement system are shown in Fig. 2.

Combing the above new strain measurement system with the digital image correlation (DIC) that is highly effective in measuring the strain field on the surface of a structure [21–23]: both the strain field of reinforcement inside a beam and that of concrete on the side-face of a beam can be obtained. These detailed strain fields provide more comprehensive data and observations than those that could possibly be obtained in conventional RC beam tests. This paper reports the results of RC beams tests carried out by using the above method.

2. Description of the experimental program

2.1. Test specimens

The experimental program involved testing of seven RC beams with a cross-section of 250 mm (width) × 300 mm (depth). The

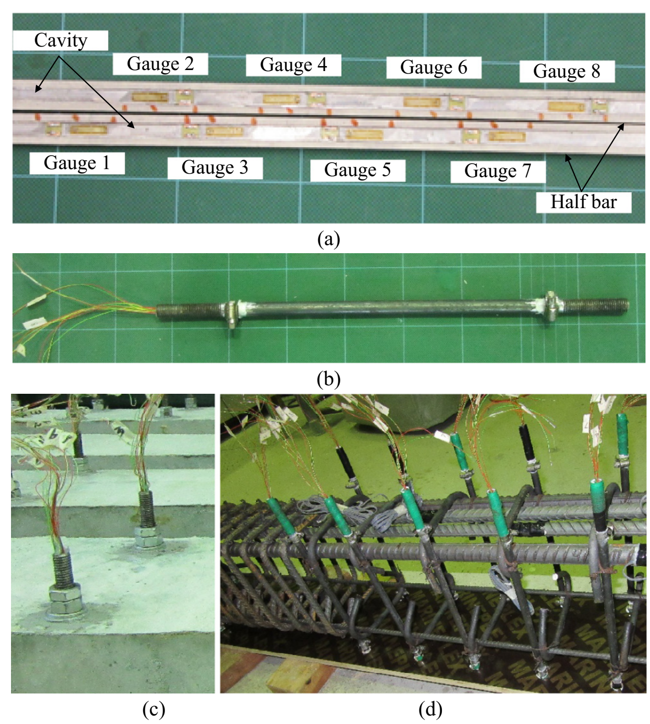

Fig. 2. Processing of shear reinforcement: (a) strain gauging system; (b) rejoined bars with strain gauges installed inside; (c) anchorage of shear reinforcing bars; (d) typical steel cage.

maximum aggregate size (10 mm and 20 mm) and type of transverse reinforcement (deformed and plain round steel bars) are the main test variables. All the beams have the same length, and the shear span-to-depth ratio (a/d) sets at 2.6. Details of the typical RC beam are provided in Fig. 3(a) and the typical reinforcement cage is shown in Fig. 2(d). The mechanical properties of the transverse and longitudinal reinforcing bars are summarized in Table 1.