Engineering Structures 76 (2014) 371–382

Contents lists available at ScienceDirect

Engineering Structures

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

Effective stiffness of reinforced concrete coupling beams

Ngoc Son Vu, Bing Li *, Katrin Beyer

School of Civil and Environmental Engineering, Nanyang Technological University, Singapore 639798, Singapore
Civil Engineering Institute, Ecole Polytechnqiue Fédérale de Lausanne (EPFL), Switzerland

ARTICLE INFO

Article history:
Received 30 April 2014
Revised 23 June 2014
Accepted 10 July 2014
Available online 8 August 2014

Keywords:
Reinforced concrete coupling beam
Diagonally reinforced concrete coupling beam
Conventionally reinforced concrete coupling beam
Initial stiffness
Stiffness ratio
Shear stiffness

ABSTRACT

Reinforced concrete (RC) structural walls with coupling beams are widely used as the primary lateral-load-bearing elements in high-rise building structures. Many researches have shown that there is uncertainty in the estimation of the effective stiffness of RC coupling beams. In an attempt to develop rational approaches regarding the stiffness of these structural components, this paper presents the analytical approaches, considering the influence of flexural and shear deformations, to determine the effective stiffness of RC coupling beams. A comprehensive parametric study, including 144 combinations for the conventionally reinforced concrete coupling beam (CCB) and 48 combinations for the diagonally reinforced concrete coupling beam (DCB), is carried out and two equations to estimate the effective stiffness of RC coupling beams are proposed each as a function of aspect ratio, transverse reinforcement ratio, longitudinal reinforcement ratio, diagonal reinforcement ratio and concrete compressive strength, on the basis of these parametric case studies. The proposed analytical approaches and the equations for assessing the effective stiffness of CCBs and DCBs are then verified by comparison with experimental results obtained from literature.

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1. Introduction

In seismic design, a displacement-based approach recently has been widely employed instead of a traditional force-based approach in which the deformation of structures is the point of focus [1]. In these structures, the effective stiffness of RC coupling beams plays an important role in the seismic performance of the structural walls and the whole structure because it may significantly affect the determination of fundamental period, displacements, ductility factor, and distributed internal forces of structures. Therefore, accurately assessing the effective stiffness of RC coupling beams is extremely important for the practical design of building structures subjected to seismic excitation. Many researchers showed that there is a large uncertainty with regard to the effective stiffness of RC coupling beams when subjected to seismic excitation. To deal with this problem, some current design codes employ a stiffness reduction factor of value from 0.3 to 0.5 of the inertia moment of the gross sectional area. However, in many cases, this simplification often leads to overestimation of the effective stiffness of RC coupling beams subjected to lateral loads. Paulay and Priestley [2], Standards New Zealand – NZS 3101 [3], and Taranath [4] recommended equations to estimate the effective stiffness of RC coupling beams as a function of the aspect ratio. These equations are oversimplified because the effective stiffness of RC coupling beams depends significantly on, not only the aspect ratio but also the reinforcement content and the concrete compressive strength. This paper presents proposed methods to estimate the effective stiffness of the RC coupling beam that would consider the influence of the flexural and shear deformation on its stiffness. Following which a parametric study based on the proposed methods is carried out to investigate the influence of some important parameters, including the aspect ratio, longitudinal reinforcement ratio, diagonal reinforcement ratio, transverse reinforcement ratio, and concrete compressive strength. Two simple equations to estimate the effective stiffness of CCBs and DCBs are also proposed based on the comprehensive parametric study. The accuracy of the proposed approaches and the equations are then verified by comparison with experimental results from literature.

2. Review of existing effective stiffness models

2.1. ACI 318-11 [5]

According to ACI 318-11 [5] there are two options for estimating the effective stiffness of flexural members: (a) $0.35E_cI_g$; or (b) it can be determined using the following equation:

$$I_e = (0.1 + 25\rho_s)\left(1.2 - 0.2\frac{b}{d}\right)I_g \leqslant 0.5I_g \tag{1}$$

* Corresponding author at: School of Civil and Environmental Engineering, Nanyang Technological University, Singapore 639798, Singapore. Tel.: +65 67905090.
E-mail address: cbli@ntu.edu.sg (B. Li).

http://dx.doi.org/10.1016/j.engstruct.2014.07.014
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Nomenclature

A_v	effective shear area, $A_v = bd_v$
A_v^*	effective area of the concrete strut, taken as $A_v^* = 0.35bd$
A_s	sectional area of longitudinal reinforcement
A_{sd}	sectional area of diagonal reinforcement
b	web width of the coupling beam
d	effective depth of the coupling beam
d_b	the effective shear depth taken as flexural lever arm which need not be taken less than 0.9d
E_c	modulus of elasticity of concrete
E_s	modulus of elasticity of reinforcing bars
f_{ct}	concrete tensile strength
f_c'	concrete compressive strength
f_y	yield strength of longitudinal reinforcing bars
I_e	effective moment of inertia of the coupling beam
I_g	moment of inertia of the gross sectional area
K_i	initial stiffness of RC coupling beams
K_{ca}	shear stiffness of constant truss angle model for CCBs
K_{va}	shear stiffness of variable angle truss model for CCBs
K_s	shear stiffness of the CCB
l	length of the coupling beam
l_d	anchorage length of longitudinal reinforcement in the CCB or diagonal reinforcement in the DCB
l_p	equivalent plastic hinge length
M_y	yield bending moment
n	modulus ratio, $n = \frac{E_s}{E_c}$
V_s	shear force transmitted by the coupling beam
V_y	yield lateral force
α	corner-to-corner diagonal angle of VATM, $\alpha = \arctan(d_b/l)$
α_d	angle of inclination of diagonal reinforcement
β	factor allowing for deformation within the anchorage length of the CCB
Φ_b	diameter of longitudinal reinforcement
ϕ_y	curvature at yield lateral force
θ	angle of the inclined strut in the cracked concrete with respect to longitudinal axis of RC coupling beam in VATM
θ_0	angle of the inclined strut in the cracked concrete with respect to longitudinal axis of RC coupling beam in CATM
Δ_{fy}	flexural and bar slip deformations (displacements, distortion) of CCBs under yield force
Δ_{f1}	flexural deformation of VATM due to the applied unit shear force
Δ_{sy}	shear deformation of the CCB under yield force
Δ_s	vertical displacement between two faces of the DCB under the shear force, V_s
υ	Poisson's ratio
μ	ductility of RC coupling beams
ζ_d	factor allowing for deformation within the anchorage length of the DCB
ρ_s	the longitudinal reinforcement ratio
ρ_v	transverse reinforcement ratio
ρ_{sd}	diagonal reinforcement ratio
γ_{s1}	shear rotation due to (caused by, under) the applied unit shear force
γ_{f1}	flexural drift angle due to (caused by, under) the applied unit shear force
γ_s	rotation of the DCB under the shear force, V_s
τ	bond stress between reinforcing bars and concrete
κ	dimensionless stiffness factor of RC coupling beams, $\kappa = \frac{I_e}{I_g}$
κ_{CCB}	dimensionless stiffness factor of CCBs
κ_{DCB}	dimensionless stiffness factor of DCBs

where ρ_s is the longitudinal reinforcement ratio; d is the effective depth of the member and b is the web width of the member.

2.2. FEMA 356 [6] & ASCE 41 [7]

FEMA 356 [6] suggests the effective stiffness be taken as $0.5E_cI_g$ for members under bending; Otherwise, ASCE 41 [7] including supplement #1 recommends a lower value for the effective stiffness of $0.3E_cI_g$.

2.3. NZS 3101 [3]

The Standards New Zealand – NZS 3101 [3] recommends an equation to estimate the effective stiffness of CCBs solely as a function of the aspect ratio:

$$I_e = \frac{0.4I_g}{1 + 8\left(\frac{d}{l}\right)^2} \tag{2}$$

NZS 3101 [3] also gives an equation estimating the effective stiffness of DCBs that depends on the aspect ratio and the expected ductility demand, μ, as follow:

$$I_e = \frac{A^* I_g}{B + C^*\left(\frac{d}{l}\right)^2} \tag{3}$$

where A, B, and C coefficients vary with μ (A = 1.0 and 0.40; B = 1.7 and 1.7; and C = 1.3 and 2.7; for μ = 1.25 and 6.0).

2.4. Paulay and Priestley [2]

Paulay and Priestley [2] propose the equation shown in Eq. (4) to calculate the effective stiffness of CCBs with depth d and clear span l

$$I_e = \frac{0.2I_g}{1 + 3\left(\frac{d}{l}\right)^2} \tag{4}$$

Paulay and Priestley [2] also suggest Eq. (5) to estimate the effective stiffness of DCBs as:

$$I_e = \frac{0.4I_g}{1 + 3\left(\frac{d}{l}\right)^2} \tag{5}$$

Eqs. (4) and (5) are also adopted by the Canadian Concrete Standard A23.3 [8]

2.5. Taranath [4]

Taranath [4] gives an equation to calculate the effective stiffness of RC coupling beams of shear walls that takes into account the effect of shear deformation in RC coupling beams as follows:

$$I_e = \frac{I_g}{1 + 2.4\left(\frac{d}{l}\right)^3(1 + \upsilon)} \tag{6}$$

where υ is Poisson's ratio. Fig. 2 illustrates the variation of the effective stiffness ratio of the CCB and DCB versus the aspect ratio for different existing effective stiffness models.

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