Engineering Structures 153 (2017) 191–204

Contents lists available at ScienceDirect

Engineering Structures

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

Fiber beam-column model for diagonally reinforced concrete coupling beams incorporating shear and reinforcement slip effects

Ran Ding[a], Mu-Xuan Tao[b], Xin Nie[a,*], Y.L. Mo[c]

[a] Key Lab. of Civil Engineering Safety and Durability of China Education Ministry, Dept. of Civil Engineering, Tsinghua University, Beijing 100084, China
[b] Beijing Engineering Research Center of Steel and Concrete Composite Structures, Tsinghua University, Beijing 100084, China
[c] Dept. of Civil and Environmental Engineering, University of Houston, Houston 77204, USA

ARTICLE INFO

Keywords:
Fiber beam-column model
Diagonally reinforced concrete coupling beams
Seismic analysis
Hysteretic behavior
Nonlinear shear behavior
Reinforcement slip

ABSTRACT

Due to the improved energy-dissipation and deformation capacity compared to the conventionally reinforced concrete (RC) coupling beams, diagonally RC coupling beams are recommended by the ACI 318 code especially for a span-to-depth ratio of less than two and thus acquire more and more applications in coupled wall and core tube systems for tall buildings. This paper proposes a sufficiently accurate and efficient displacement-based fiber beam-column model for the nonlinear seismic analysis of diagonally RC coupling beams with span-to-depth ratios ranging between one and five. The model is developed on the platform of a general FEA package MSC.Marc. First, the conventional fiber beam-column element is modified to consider the flexural contribution of diagonal bars. Then the new section shear force-shear distortion and slip deformation rules are proposed and incorporated into the modified fiber element, respectively, since both the shear and reinforcement slip are critical mechanisms influencing the seismic performance of the beam. The equations for critical model parameters including the cracked shear stiffness and chord rotation limit are developed and verified based on the results of sixteen test specimens collected from previous research. The model is utilized to simulate the collected specimens together with a coupled wall system and proves to be a powerful tool for the nonlinear seismic analysis of diagonally RC coupling beams and coupled walls with satisfied accuracy, efficiency and modeling convenience.

1. Introduction

Nowadays reinforced concrete coupled walls and core tubes have become the most popular structural system for tall buildings due to their efficient resistance to seismic actions and compatibility with architectural requirements. In a coupled wall structural system the coupling beams are key components, which contribute significantly to structural stiffness under frequent earthquakes and energy dissipation during severe earthquakes. Numerous efforts have been devoted to investigating the seismic behavior and improving the seismic performance of RC coupling beams [1–14].

Among all kinds of RC coupling beams, in practice the beams with conventional and diagonal reinforcement layouts are the most widely used. Compared with the coupling beams constructed with reinforcement scheme similar to frame beams (Fig. 1[a]), it is confirmed by many test results that the diagonal reinforcement layout (Fig. 1[b]) that was first introduced by Paulay and Binney [3] benefits the coupling beam with significantly a higher deformation and energy-dissipation capacity [3–11], as illustrated by Fig. 1(d). In addition, ACI 318-14 [15] introduced an alternative detailing option, as shown in Fig. 1(c), where transverse reinforcement is placed to confine the entire beam cross section instead of the diagonal bar bundles. Consequently the construction of a diagonally RC coupling beam is greatly simplified.

Recently, the nonlinear dynamic analysis has gained increasing attention and application in the performance-based seismic design of tall buildings, which requires nonlinear models for all structural members with adequate accuracy, efficiency and numerical stability. Displacement-based fiber beam-column elements have been successfully used to model the frame beams and columns due to their simplicity and accuracy [16,17]. However, the diagonally RC coupling beams featured with complex hysteretic behavior cannot be reasonably simulated by the conventional fiber model. It is thus necessary to develop an enhanced fiber model for the seismic structural analysis of coupling beams in tall buildings that is capable of considering the nonlinear shear and reinforcement slip effects and still keeps the simplicity and convenience of the original fiber model.

To date, several researchers have reported macro models for diagonally RC coupling beams based on springs, hinges and line elements

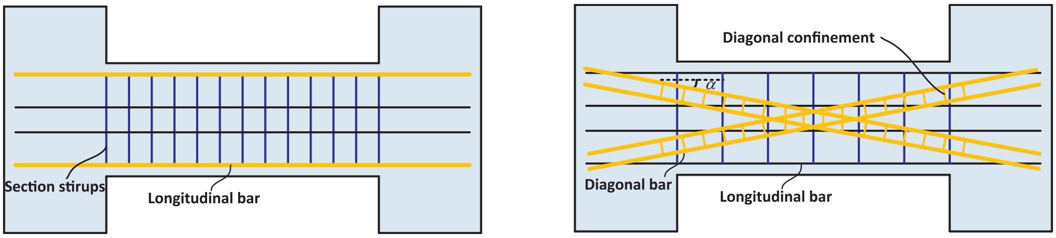
---

* Corresponding author.
E-mail address: xinnie@mail.tsinghua.edu.cn (X. Nie).

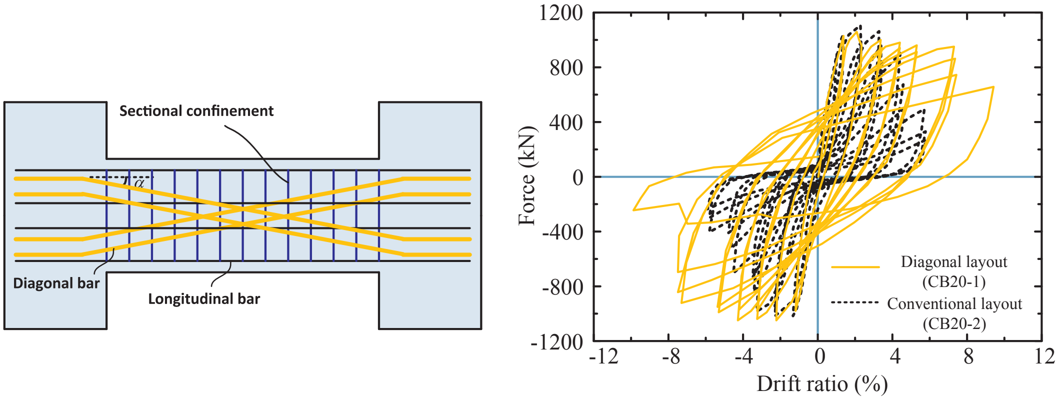
http://dx.doi.org/10.1016/j.engstruct.2017.10.035
Received 16 June 2017; Received in revised form 11 October 2017; Accepted 12 October 2017

Nomenclature

A	area of the coupling beam section
A_{sd}	sectional area of diagonal reinforcements
A_{sv}	sectional area of section confining transverse reinforcement
b	width of the coupling beam
d	effective depth of the coupling beam
D_d	diameter of diagonal bars
D_l	diameter of top or bottom longitudinal bars
E	concrete elastic modulus
f_c'	cylinder concrete compressive strength
f_{sd}	current stress of the diagonal bars
f_{yd}	yield strength of the diagonal bars
f_{yl}	yield strength of top or bottom longitudinal bars
G	concrete shear modulus $= E/2(1+\nu)$
h	depth of the coupling beam
i	counter tracing successive cycle numbers in one direction reaching current maximum strain
k_1 k_2 and k_3	shape control parameters for monotonic tensile stress-strain curves of rebar
k_{cr}	cracked shear stiffness
k_{ini}	initial shear stiffness of the shear force-shear strain skeleton curve
k_{re}	reloading reference slope
k_t	slope before the reloading turning point
l	length or span of the coupling beam
l/h	span-to-depth ratio of the coupling beam
l_e	length of elastic region for the bar anchorage
l_{py}	length of inelastic region for the bar anchorage
n_d	number of diagonal bars in each bundle
n_l	number of top or bottom horizontal bars
n_{sv}	number of legs of sectional transverse rebars
s	spacing of section confining transverse rebars
V_{cr}	shear force of the shear cracking point
V_m	shear force of unloading starting point from the skeleton curve
V_{re}	shear force of reloading beginning point
$V_{sd,i}$ $V_{ssd,i}$	shear force of strength deterioration point
V_{un}	shear force of unloading starting point from the other curves
α	inclination angle of diagonal bars
β	the shear stiffness reduction factor
δ_{ext}	slippage of the bar caused by strain accumulation along the development length
δ_{imit}	slip corresponding to γ_{imit}
δ_m	slip deformation of strength deterioration point
δ_{re}	slip of reloading beginning point
δ_t	slip of reloading turning point
δ_{un}	slip deformation of unloading starting point from other curves
$\delta_{un,m}$	slip deformation of unloading starting point from the skeleton curve
ε_s	current strain of the diagonal bars
ε_y	yield strain of the diagonal bars
γ_{cr}	shear strain of the cracking point at the shear skeleton curve
γ_{limit}	drift ratio at strength degradation
γ_m	shear strain of the strength deterioration point
γ_{re}	shear strain of reloading beginning point
γ_t	shear strain of reloading turning point
γ_{un}	shear strain of unloading starting point from other curves
$\gamma_{un,m}$	shear strain of unloading starting point from the skeleton curve
θ_{ext}	angle of the slip-induced crack at the beam ends
ρ_{sv}	ratio of section confining transverse reinforcement, $\rho_{sv} = n_{sv}A_{sv}/bs$
ρ_{sd}	ratio of diagonal reinforcements, $\rho_{sd} = n_d A_{sd}/bh$
ν	concrete Poisson's ratio = 0.17



(a) Conventional layout (b) Traditional diagonal layout



(c) Improved diagonal layout (d) Typical hysteretic curves

Fig. 1. Comparison of RC coupling beams with different reinforcement layouts.