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# Strut-and-tie model for interior RC beam-column joints with substandard details retrofitted with CFRP jackets

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ABSTRACT

A softened strut-and-tie model (STM) is developed for interior reinforced concrete (RC) beam-column joints without any steel hoops in the joint or intermediate longitudinal column steel reinforcement, and discontinuous bottom beam flexural steel reinforcement. The STM model is extended to identical joints retrofitted with Carbon Fiber-Reinforced Polymer (CFRP) composites. The STM model is compared to experiments of two full-scale RC beam-column interior joints, one of which was retrofitted with CFRP composites. Failure modes for the original joint included anchorage failure of bottom steel beam bars, crushing of concrete nodal zones, diagonal joint shear failure, and for the retrofitted joint CFRP laminate delamination and crushing of joint core concrete. The STM model is based on the joint reinforcement details and experimental performance, including column axial load effects and the contribution of CFRP horizontal and diagonal laminates as tension ties. STM model assumptions were verified with strain gauge measurements. The STM model was successful in estimating the ultimate shear strength of the original and retrofitted joints. Recommendations are presented for evaluating the strut width for both original and retrofitted joints that include the quality of the bond of beam steel reinforcement to concrete in the beam-column joint.

## 1. Introduction

The design of reinforced concrete structures before modern seismic codes did not consider the effects of seismic loading on joint dimensions and steel reinforcement details. Deficiencies include the absence of confining steel hoops, absence of intermediate longitudinal column steel reinforcement, and insufficient anchorage details of steel reinforcing bars at the bottom of the beam extending into the beam-column joint. Current recommendations for design of beam-column connections in monolithic reinforced concrete structures are provided in modern codes from guide documents such as the ACI Committee 352 Recommendations [1].

Several researchers have conducted experiments to investigate seismic retrofit of deficient interior beam-column joints using different layouts of bonded FRP composites [2–7]. A number of methods for the design of FRP composite materials for retrofit of RC beam-column joints have also been developed [8–12]. A method for seismic retrofit design of substandard beam-column joints with FRP composites using the strut-and-tie model (STM) has not yet been developed.

In disturbed regions, linear strain distribution does not apply and new methods have been developed for shear design [13]. The strut-and-tie model (STM) is an effective shear design method based on the lower-bound plasticity theorem, and is currently included in the ACI 318 Building Code [14]. The significance of the method is that in disturbed regions, the STM model can predict the shear strength of members with better accuracy than traditional flexure theory. A significant amount of research on the STM method has focused on deep beams and shear walls. However, there are important differences in internal stress flow between beam-column joints and deep beams due to different boundary conditions. The STM method has been applied to RC exterior and interior beam-column joints with seismic code conforming details [15,16]; in addition, a softened STM model has been developed using a softened stress-strain curve of the cracked concrete in compression [17]. The effect of high axial load on seismic behavior of RC beam-column joints has also been considered using a softened STM model [18].

There is limited application of the STM model in RC structures rehabilitated with FRP composites [19–24]. In this investigation,

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**Nomenclature**

| | |
|---|---|
| $a_b, a_c$ | depth of compression zone in beam and column |
| $a_s$ | depth of diagonal concrete strut |
| $A_{gc}$, $A_{gc}$ | beam and column gross cross-sectional area |
| $A_{sth}, A_{stv}$ | area of horizontal and vertical steel reinforcement in the joint |
| $b_s$ | width of diagonal concrete strut |
| $A_{str}$ | cross-sectional area of diagonal concrete strut |
| $C_{dn}$ | nominal joint diagonal compression strength |
| $d_b$ | diameter of beam steel bars |
| $E_f$ | elastic modulus of unidirectional CFRP composite |
| $f'_c$ | concrete compressive strength |
| $f_{smax}$ | maximum stress in beam reinforcing steel |
| $f_y$ | steel yield strength |
| $F_h$, $F_v$ | horizontal and vertical tension tie force |
| $\overline{F_h}$, $\overline{F_v}$ | balanced amount of horizontal and vertical tie force |
| $F_{hFRP}, F_{vFRP}$ | horizontal and vertical tension tie force from CFRP composite laminates |
| $F_{hsteel}, F_{vsteel}$ | horizontal and vertical tension tie force from steel bars |
| $h_b$, $h_c$ | beam and column width |
| $l_a$ | embedment of the beam steel bars |
| $l_h$, $l_v$ | internal lever arms of horizontal and vertical shear couple |
| $n_{fh}, n_{fv}$ | number of horizontal and vertical CFRP layers |
| $N_b$, $N_c$ | beam and column axial load |
| $t_f$ | thickness of one CFRP layer |
| $T_{fhi}$, $T_{fvi}$ | horizontal and vertical tension force from CFRP laminate |
| $\bar{u}$, $\bar{u}_{as}$, $\bar{u}_r$ | bond stress, bond stress for original joints, bond stress for retrofitted joints |
| $V_{jh}$ | horizontal joint shear |
| $W_{fh}$, $W_{fv}$ | effective width of horizontal and vertical CFRP laminate |
| $\alpha$ | inclination of unidirectional fibers with respect to horizontal |
| $\gamma_h, \gamma_v$ | fraction of diagonal compression transferred by horizontal and vertical tie |
| $\epsilon_{feh}$, $\epsilon_{fev}$ | experimental strains of the CFRP laminate in the horizontal and vertical direction |
| $\zeta$ | concrete softening coefficient |
| $\theta$ | angle of inclination of the diagonal strut |
| $k$ | approximate strut-and-tie index based on combination of shear mechanisms |
| $k_d$ | diagonal strut index |
| $\underline{k_h}$, $\underline{k_v}$ | approximate horizontal and vertical strut-and-tie index |
| $\overline{k_h}$, $\overline{k_v}$ | additional contribution of sufficient horizontal and vertical tie |

the STM model is used to analyze original and CFRP composite retrofitted interior RC beam-column joints with substandard steel reinforcement details. Experiments are used to validate the STM model developed with respect to the ultimate shear strength of the original and retrofitted joints. The STM model developed is based on the joint steel reinforcement details, cracking patterns and experimental performance of the beam-column joints tested in this research. However, the STM model presented in this paper is general and could be extended to beam-column joints with different steel and CFRP retrofit details.

## 2. Description of original and retrofitted RC interior beam-column joints

### 2.1. Original beam-column joints

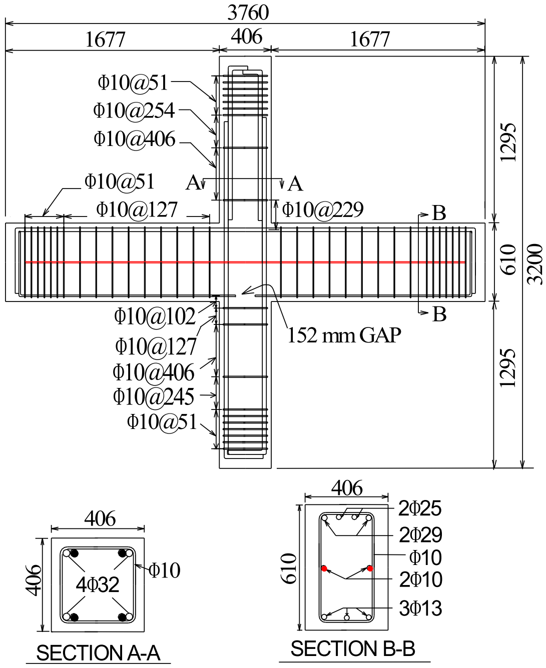

**Fig. 1.** Interior beam-column joint dimensions and steel reinforcement.

The details of an original and a retrofitted beam-column joint are briefly summarized. A more comprehensive description of the experiments considered in this study, which included eight large-scale tests of beam-column joints with different details including beams with various depths, can be found elsewhere [4]. The joint dimensions and steel reinforcement details of the interior beam-column joints considered in this paper are presented in Fig. 1. The three 13-mm beam bottom steel bars shown in Section B-B of Fig. 1 have an embedment into the joint which is only 29% of the required development length for beam-column connections per ACI 352 [1]; in addition these bars have no hooks. To limit bar slippage within the joint, ACI 352 recommendations require that all straight beam bars passing through the joint should have a diameter smaller than 1/20 of the column depth and a similar requirement exists for column bars compared to the beam depth; in both cases the steel reinforcement details of these beam-column joints do not conform to this requirement. The influence of bond performance of steel bars to concrete is known to be an important factor in the seismic performance of beam column joints. The center-to-center spacing between layers of horizontal hoop steel reinforcement, required for connections that are part of the primary system for resisting seismic lateral loads, should not exceed the least of 1/4 of the minimum column dimension, six times the diameter of the longitudinal column bars to be restrained, or 150 mm; this requirement is not met since no transverse steel hoops were provided in the joint core of the beam-column joints in the present investigation.

According to the ASCE/SEI 41-13 Standard [25] the joint shear demand, based on the theoretical beam flexural capacity, is higher than the capacity of the interior joints tested in this paper without