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Eccentricity-based design procedure of confined columns under compression and in-plane bending moment

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A R T I C L E I N F O

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A B S T R A C T

Steel strapping tensioning technique (SSTT) has started to gain attention recently. The confining method using post-tensioned recycled steel straps allows high-strength concrete (HSC) columns to achieve higher ultimate strength and ductility. However, the experimental data and design method for SSTT-confined columns subjected to eccentric compression is still lacking and its behavior is needed to be clarified before it can be used confidently in the industry. In this paper, theoretical analysis was carried out considering various parameters such as eccentricity ratio, confining volumetric ratio and end eccentricity ratio of such columns. Experimental tests were carried out to validate the developed theoretical model. Finally, the equivalent concrete stress block parameters of circular SSTT-confined members are theoretically studied and the modified values are purposely suggested for the calculation of capacity interaction diagram. Comparisons between the proposed design equations with theoretical results showed accuracy as high as 95%.

1. Introduction

In conventional reinforced concrete (RC) columns, there are possibilities that the concrete cover can be spalled off and reinforcements can be buckled during the earthquake. To avoid this catastrophic behavior, confinement is generally required especially for high-strength concrete (HSC), which is brittle in nature [1–4]. However, it has been consistently being reported that the ductility requirement for a short RC column is unlikely to be met by simply increasing the transverse steel ratio [5,6].

Recently, an external confining method by using low-cost recycled steel straps (available in the packaging industry) has been developed [7,8]. The confining method is termed as steel strapping tensioning technique (SSTT) for brevity hereafter. The steel straps are post-tensioned around HSC columns and secured by using self-regulated end clips to avoid early loss of post-tensioned stress. Both previous experimental and numerical tests have confirmed the applicability of the method in increasing the strength and ductility of HSC columns. Fig. 1 illustrates the HSC columns confined with SSTT confinement. The SSTT-confinement serves two main purposes: (1) enhances the axial strength and deformability of the RC columns through restriction of lateral expansion; and (2) prevents the concrete cover from spalling off and protects the longitudinal bars from buckling. Generally, there are two major types of confinement in concrete: passive and active confinement. For passive type confinement, the confining stress is initiated when the concrete starts to dilate laterally. However, this type of confinement has been found to be less suitable in confining HSC columns, where HSC normally exhibit very small Poisson's ratio. Meanwhile the active confinement allows the effective confining pressure around the concrete even before the concrete starts to dilate. The confinement using SSTT is active type, as it allows post-tensioning stress around the concrete before the load is applied [9].

Previously, a number of research have been performed to investigate the effectiveness of using post-tensioned steel straps in confining concrete columns [10–13]. However, the steel straps were secured by using clip notch and it is believed that effective confining pressure will loss during the lifting of the slip notch. In addition, the previous tests have mainly concentrated in increasing the ultimate strength of normal strength concrete (NSC) columns. In Universiti Teknologi Malaysia (UTM), an innovative end clip has been proposed, where it can prevent the loss of effective confining pressure without the need to lift the notch. The proposed end clips also allow the steel straps to be self-regulated between layers, which can uniformly distributes the confining stresses among each layers. Besides, UTM has focused on using the SSTT confinement in increasing the ductility of HSC columns, rather than the ultimate strength of NSC columns. In their tests, it has been proven that SSTT confinement can be effective in increasing both strength and ductility of HSC cylinders. [14] studied on the effects of

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Nomenclature

A	Area of compression zone
A_{si}	cross sectional area of longitudinal bars
A_{sc}	area of compressive steel
α_1	mean stress factor
β_1	block depth factor
C_c	curvature compression zone
C_s	Steel compressive strength
D	Column diameter
d_{si}	location of longitudinal tensile bar from extreme concrete fiber
dl	thickness of layer
dL	segmented column length
E_s	elastic modulus of steel
E_c	Elasticity of concrete
E'_{sec}	secant modulus of confined concrete at peak stress
e_i, e_s	end eccentricities, with e_i has larger absolute value
ε_{cj}	extreme fiber concrete strain
ε'_{cc}	strain at confined concrete strength
ε'_{cu}	ultimate strain of confined concrete
ε_{co}	ultimate concrete strain
ε_s	strain of steel
ε_y	yield strain of steel
ε_{sy}	yield strain of longitudinal steel
ε_{ci}	concrete strain at a given stress
f_{sy}	yield stress of longitudinal steel
f_{ci}	concrete compressive stress at a given strain
f'_{cc}	confined concrete compressive strength
f_{co}	unconfined concrete compressive strength
L	column length
M_c	moment contributed by concrete
M_u	ultimate moment of column
M_{step}	Bending moment at a given stage
N_u	ultimate load of column
N_{step}	axial load at a given stage
P_i	moment arm from *i*-th layer to neutral axis
ρv	confining volumetric ratio
R	Column radius
T	tensile force
V_s	volume of confining steel straps
V_c	volume of confined concrete
y_i	with of *i*-th layer
σ_{st}	stress in tension longitudinal steel
σ_{si}	stress of longitudinal steel bar at *i*-th layer
ϕ_j	curvature
x_n	neutral axis
δ	lateral deflection
σ_{sc}	stress in longitudinal steels

beyond ductility and concrete stress-strain curve to obtain complete stress-strain curves for unconfined and SSTT confined concrete cylinder. The short-term durability of SSTT confined concretes were investigate of different degree of corrosion in different environment [15]. The bond strength of the SSTT confined normal strength concrete was compared with 3 different group of confinement [16]. The failure mode of the confined cylinders is gentler compared with plain cylinder [17]. [18] investigated the slenderness effects of SSTT-confined HSC columns and concluded that the confinement has great tendency to alter the behavior of short columns to behave similarly to slender columns. [19] conducted experiments to investigate the optimum utilization of SSTT confinement and proposed the maximum slenderness ratio of HSC columns expected to be beneficial from the confinement. Recently, a series of experimental studies to investigate the axial compression behavior SSTT-confined HSC columns with square sections were conducted by [7] and the procedure to estimate ultimate capacity of such columns have been proposed. In this paper, theoretical analysis is performed to investigate the behavior of short circular SSTT-confined HSC columns subjected to eccentric compression. The confined concrete stress block parameters for such columns were suggested. Interaction diagram obtained through the proposed concrete stress blocks are verified via experimental and theoretical model. Recently, the confining works mainly focus on the passive confinement on short column, however the more effective active confinement was used in this paper to confine short column. SSTT confinement represented active confinement which allowed the pre-tensioning of steel straps laterally confine short column.

Fig. 1. HSC columns confined with post-tensioned steel straps.

2. Numerical investigation

2.1. Constitutive material

A theoretical model was developed to describe the behavior of SSTT-confined HSC columns. The model follows the numerical iterative method, which was originally proposed by [20]. This method has been widely used in simulation of RC columns [21,22], steel column [23], Composite column [24,25] and FRP-confined RC column [26].

The simulated confined column can be be subjected to two end eccentricities, namely e_i and e_s respectively. The value of e_s is the end eccentricities that always has greater absolute value whilst e_i has the smaller absolute value. The length of the column, L is segmented into equal units of dL. The curvatures are then calculated at each segment along the length L of the column. The following assumptions were considered during the simulation:

i) Plane section remains plane after bending.
ii) A perfect bond is assumed between internal longitudinal reinforcement with the concrete.