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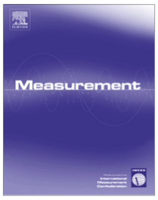

Flexural ductility design of confined high-strength concrete columns: Theoretical modelling

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ABSTRACT

Since the past few decades, high-strength concrete (HSC) has found increasingly wide applications in civil and structural engineering. Its utilisation is needed for the construction of buildings where reductions in self-weight and size of structural members are important. However, it was consistently reported that HSC exhibits undesirably lower ductility with the increase of concrete compressive strength. To restore the ductility, additional confinement has been recommended. This paper investigates the effectiveness of using Steel-Strapping Tensioning Technique (SSTT) to increase the flexural ductility of HSC columns. The effects of SSTT-confinement on the flexural ductility of HSC columns is studied by non-linear moment–curvature analysis. Based on such analysis, a parametric study was conducted to investigate the effects of various parameters, such as normalised axial force, normalised neutral axis depth, concrete compressive strength and confining volumetric ratio, on the flexural ductility of such columns. The results revealed that the flexural ductility of HSC columns is highly dependent on normalised axial force and neutral depth axis of the columns. It was found that the flexural ductility design of SSTT-confined HSC columns can be simplified by controlling the maximum allowable values of these parameters. Finally, two design equations were proposed for the flexural ductility design of such columns.

1. Introduction

Ductility is generally regarded as important as strength in the building construction particularly in seismic regions [20,4,18,17,8]. When a ductile structure is overloaded or subjected to cyclic loads, plastic hinge have to be created at critical regions. This allows the redistribution of maximum moment from critical region to other regions without overall collapses. Hence, structures with adequate ductility would provide better chance of survival during extreme events. Ductility has been neglected in the past, especially in the design of reinforced concrete (RC) structures which were built of normal strength concrete (NSC). In this design, nominal ductility is assumed by the deemed-to-satisfy rules in the existing design codes.

Recently, high-strength concrete (HSC) has become increasingly popular due to the innovation in concrete technology. In fact, the use of HSC allows the member size to be significantly reduced. However, it was consistently reported by the past research that HSC is more brittle than NSC. The columns made with HSC were also found to have failed in sudden and explosive manner [12]. In view of this, a confining method namely steel strapping tensioning technique (SSTT) was proposed to confine HSC. As existing conventional confining methods are passive in nature, they were found to be unsuitable to be used to confine HSC. This confining technique involves the post-tensioning of low-cost recycled steel straps around the circumferential surface of HSC columns, in order to ensure effective

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Notation

A_{si}	corresponding cross-sectional area of longitudinal steel bar
A_{st}	total cross-sectional area of longitudinal bars
D	diameter of column section
dl	thickness of each layer of discretized column section
dL	length of column segmented unit
d_{si}	location of longitudinal tensile bar from the extreme concrete fibre
E_c	tangent modulus of elasticity of concrete
E'_{sec}	secant modulus of confined concrete at peak stress
E_s	elastic modulus of steel
ε_{co}	ultimate strain of unconfined HSC
ε'_{cc}	peak strain of confined concrete
ε_s	steel strain
ε_y	yield strain of steel
ε_{ci}	concrete strain
ε_{cc}	axial compressive strain of concrete
f_{ci}	concrete stress at a given strain
f_{cu}	concrete compressive strength
f_y	yield strength of steel
f_{ys}	yield strength of steel straps
L	column length
M	moment of column
M_u	ultimate moment of column
μ	ductility
N_u	ultimate load at failure
N_{ult}	ultimate load capacity of column under concentric load
$N/f'_{cc}A_c$	normalised axial force
X_n/D	normalised neutral axis depth
R	radius of column section
V_s	volume of steel straps using the SSTT
V_c	volume of concrete
x	ratio of axial compressive strain to concrete peak strain
x_n	neutral axis depth
y_i	width of i-th layer
ρ_v	confinement volumetric ratio of steel straps
ρ_t	internal tensile reinforcement ratio of column
ρ_c	internal compressive reinforcement ratio of column
ϕ	curvature
σ_{si}	stress of longitudinal bar at i-th layer

confinement prior to the application of loading. The details of the confining procedure and its positive results can be found widely elsewhere [12,13,11,7,15]. It was consistently being reported that this confining method can improve the strength and ductility of HSC columns significantly. The failure mode of such confined columns was also reported to be more ductile compared with unconfined counterparts.

The flexural ductility of SSTT-confined HSC column can be evaluated based on its non-linear moment–curvature curve extended into the post-peak range. In this study, the developed theoretical model based on a previous work by Ma et al. [14] is adopted. The model is capable to simulate the confinement effects and non-linearity of the confined concrete. It has been validated and proven to be satisfactorily accurate in simulating the moment–curvature behaviour of such columns. It is seen as a robust tool as it provides an analytical approach for evaluating the flexural ductility of SSTT-confined HSC columns without extensive laborious tests.

A parametric test is conducted to investigate the combined effects of various parameters on the flexural ductility of such columns. Based on the analysis, a set of expression for flexural ductility design is proposed. Comparisons are made with theoretical results to check the reliability of the proposed equations. Although it is a norm to provide confinement in HSC columns, there are still no existing design codes which has clearly stipulated the amount of confinement needed. Hence this study is particularly important to be used as a guideline for the flexural ductility design of SSTT-confined HSC columns.

2. Numerical procedure

2.1. Properties model of concrete and steel

In this analysis, the stress–strain model which was originally proposed by Popovics [19] was used. The equation relates the axial stress, f_{ci} and axial strain, ε_c of confined concrete as follows:

$$f_{ci} = \frac{f'_{cc}x \cdot r}{r - 1 + x^r} \tag{1}$$

where $x = \varepsilon_{ci}/\varepsilon'_{cc}$; $r = E_c/(E_c - E'_{sec})$; ε'_{cc} is the strain corresponding to f'_{cc}; E_c is the elastic modulus of concrete $(4700\sqrt{f'_{cc}})$; $E'_{sec} = f'_{cc}/\varepsilon'_{cc}$; f'_{cc} is determined based on the empirical equation proposed by Awang [2] as below:

$$f'_{cc} = f_{cu} \times 2.62\rho_v^{0.4} \tag{2}$$

where $\rho_v \left(= \frac{f_{ys}A_{sc}}{f_{cu}A_c}\right)$ is the SSTT-confinement volumetric ratio, f_{ys} is the yield strength of confined material, A_{sc} is the volume of confined steel used, f_{cu} is the concrete compressive strength and A_c is the volume of concrete being confined. The strain corresponding to confined concrete strength, ε'_{cc} and ultimate strain of confined concrete, ε'_{cu} are respectively evaluated based on empirical equations as below:

$$\varepsilon'_{cc} = \varepsilon_{co} \times 11.60\rho_v \tag{3}$$

$$\varepsilon'_{cu} = \varepsilon_{co} \times [8.9\rho_v + 0.51] \tag{4}$$

where ε_{co} is the ultimate strain of HSC and is assumed to be 0.004.