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Seismic performance assessment of flexure-dominate FRP-confined RC columns using plastic rotation angle

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ABSTRACT

External wrapping of fiber reinforced polymer (FRP) materials is a widely applied method for the seismic retrofit of reinforced concrete (RC) columns. The seismic evaluation of conventional reinforced concrete columns prior to retrofit is presented in ASCE 41–13 although there is little available guidance for evaluating the deformation capacity of FRP-retrofitted reinforced concrete columns. In this paper, 77 FRP-retrofitted concrete columns with flexural deficiency were collected from the published literature. The yield and ultimate rotations of all specimens were obtained from backbone curves. The relationship between yield and ultimate rotation, and column parameters was analyzed. Consistent with the approach of ASCE 41, an empirical model, which considers the variation of axial force ratio, effective transverse reinforcement ratio and shear force ratio, was proposed to predict the plastic and ultimate rotations. Results were compared with other available models and were shown to be generally more accurate for both circular and rectilinear columns, which proved the efficiency of the proposed model. Finally, a reduction parameter for the expression of plastic rotation angle was adopted to obtain the model parameter *a* required for ASCE 41-compliant modelling of FRP-retrofitted reinforced concrete columns with flexural deficiency.

1. Introduction

External confinement using fibre reinforced polymer (FRP) materials has been widely used as a means of seismic retrofit of reinforced concrete columns. Recently, provisions for this so-called 'FRP wrapping' method of seismic retrofit have been adopted into ACI 440.2R-17 *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures* [1]. Other international documents including JSCE [2], CNR-DT 200 [3], fib [4], and Concrete Society [5] also provide guidance for such retrofit measures. FRP wrapping of deficient reinforced concrete columns is an attractive retrofit measure since it has little effect on column stiffness while increasing capacity marginally and ductility significantly.

The ASCE 41-13 *Seismic Evaluation and Retrofit of Existing Buildings* (ASCE) [6] and EuroCode 8 - Part 3 (EC8) [7] provide extensive guidance for the seismic evaluation of existing concrete structures. However, both are silent on evaluating the impact of subsequent retrofits. An approach for evaluating FRP-retrofitted concrete structures is necessary to permit designers to make a reasonable prediction and assessment of the post-retrofit performance of their FRP-retrofitted concrete structures. Such an approach is also necessary for future seismic or post-event assessment when the FRP-retrofit is part of the existing structure. In order to be useful and accepted, a post FRP-retrofit assessment methodology consistent with ASCE 41 [6] is proposed which includes a significant element of Performance-based Design (PBD). The objective of this paper is to demonstrate just such an approach – using the example of FRP retrofit of flexure-dominate columns. This approach may then be extended to other retrofit applications.

Flexural failure, shear failure and lap splice failure are the common failure modes of pre-1970 (or otherwise poorly detailed) reinforced concrete columns subject to seismic loads [8]. This paper focuses on the evaluation of seismic properties of reinforced concrete columns exhibiting axial-flexural or flexure-shear dominated performance subsequently retrofitted with FRP jackets. Axial-flexural failure occurs when inadequate confinement from existing transverse reinforcement is provided in the plastic hinge zone resulting in cover concrete crushing

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Nomenclature

AAE	average absolute error
A_c	total concrete area (mm^2)
A_e	area of effectively confined region (mm^2)
A_g	gross area of column section (mm^2)
A_s	total cross section area of longitudinal steel bars (mm^2)
A_v	area of transverse steel reinforcement (mm^2)
b	cross section width (mm)
D	diameter of circular section (mm)
d	cross section depth (parallel to the load direction) (mm)
d_b	diameter of longitudinal steel bar (mm)
E_f	elastic modulus of FRP jacket (GPa)
E_s	elastic modulus of steel (MPa)
f_c'	concrete strength (MPa)
f_f	tensile strength of FRP jacket (MPa)
f_{yl}	yield stress of longitudinal steel bars (MPa)
f_{yv}	yield stress of transverse steel bars (MPa)
I	reinforcement index in [41]
k_s	shape factor
L	shear span of column (mm)
L_p	plastic hinge length (mm)
L_{p0}	plastic hinge length of conventional reinforced concrete column (mm)
M	moment at the base of column (kN·m)
m	specimen number in AAE, Mean and SD calculation
Mean	mean value of ratio of predicted to experimental data
n	axial load ratio
n_0	axial load ratio parameter in [38,39]
P	axial load (kN)
P_f	failure probability
r	corner radius of a rectilinear section (mm)
s	space of stirrup (mm)
SD	standard deviation
t_f	total thickness of FRP jacket (mm)
V	shear force corresponding to nominal flexure capacity (kN)
V_{ideal}	lateral load corresponding to the ideal flexural capacity of column (kN)
V_{y1}	lateral load when the first longitudinal steel bar yields (kN)
$\bar{\varepsilon}$	normalized FRP rupture strain in [42]
ε_0	strain of breakpoint of stress-strain curve in [42]
ε_f	rupture strain of FRP jacket
ε_{sy}	yield strain of longitudinal reinforcement
ϕ_y	yield curvature
ϕ_u	ultimate curvature
ν	shear force ratio
θ_y	yield rotation angle
θ_p	plastic rotation angle
θ_u	ultimate rotation angle
ρ_{eff}	effective transverse reinforcement ratio (%)
ρ_f	volumetric reinforcement ratio provided by transverse FRP (%)
ρ_l	longitudinal reinforcement ratio (%)
ρ_s	transverse reinforcement ratio (%)
Δ_{ideal}	displacement corresponding to the ideal flexural capacity of column (mm)
Δ_y	yield displacement (mm)
Δ_{y1}	displacement when the first longitudinal steel bar yields (mm)
Δ_u	ultimate displacement (mm)

and spalling, further loss of transverse confinement, longitudinal bar buckling, and compression failure of the concrete core. Flexural-shear failure occurs when the column develops its flexural strength, however ultimately fails in shear with flexural-shear cracks in the hinge region following the yield of longitudinal reinforcement.

To address both failure modes, external FRP jackets provide additional lateral confinement, confining not only the core but the cover concrete thereby also providing continued lateral support to the longitudinal reinforcement [9]. Wrapping FRP around the concrete column plastic moment region is an effective means of enhancing the deformation capacity of columns with flexural deficiencies. With the inclusion of additional longitudinal reinforcement, the approach can also be tailored to provide additional flexural capacity, although this is a less common objective of reinforced concrete column retrofit. A significant advantage of such FRP retrofits is that they have little or no impact on the column stiffness and therefore have no effect on the dynamic properties of the structure or the load path through the structure.

Consistent with ASCE 41 [6], plastic rotation angle, θ_p, is selected as the modelling parameter to evaluate the deformation capacity of FRP-retrofitted concrete columns. A database of FRP-retrofitted concrete columns with flexural deficiency tested under combined axial load and lateral load is presented. The database includes 77 test results of FRP-retrofitted columns from 20 experimental studies published between 1997 and 2017. This database is a valuable document for (1) evaluation of existing models predicting deformation capacity of retrofitted columns; (2) development and verification of future model and (3) future establishment of a larger database – in particular, identifying the data that must be reported so that the data may be broadly useful. The important parameters, consistent with those of ASCE 41 for conventional RC columns, which influence the ultimate and plastic rotation angle are then discussed, including axial force ratio n, shear force ratio ν and effective transverse reinforcement ratio ρ_{eff}. The relationship between the ultimate rotation θ_u, plastic rotation angle θ_p and the retrofitted column parameters is studied. The proposed model for θ_u, and θ_p, can be used for FRP retrofitted concrete columns with circular, square and rectangular sections within the range $\rho_{eff} \le 0.0145$ (as constrained by available data). The equation for ultimate rotation θ_u, resulted in the smallest average absolute error (AAE) compared to other models from the available literature. In the final part of the paper, the model parameter a (Fig. 1), required for ASCE 41 [6] seismic evaluation, is determined for flexure-dominate FRP-retrofitted concrete columns to give guidance for retrofit design. The approach presented here can be extended to other FRP-retrofitted concrete systems.

2. Database

A database [9–28], was established to investigate the influence of FRP wrapping on reinforced concrete columns with flexural deficiencies. In most studies, unretrofitted reinforced concrete columns are presented as the 'control specimen' for the FRP-retrofitted columns. In total, 33 conventional reinforced concrete (control) columns and 77 FRP-retrofitted concrete columns are included in the database. The suitability of experimental results for FRP-retrofitted concrete columns