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Influence of adjusted models of plastic hinges in nonlinear behaviour of reinforced concrete buildings

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ABSTRACT

Among the procedures available for the seismic analysis of structures, pushover analysis is one of the most frequently used methods by structural engineers. An adequate modelling of the plastic hinges generated during the pushover analysis is crucial in order to obtain accurate results. Thus, the yielding and ultimate states of the cross-section must be defined in order to model the generalised force-deformation relation of plastic hinges. For this purpose, the use of empirical expressions that obtain the aforementioned states from the cross-section properties can prove beneficial.

The main objective of this work is to study the influence of different plastic hinge models on the structural nonlinear behaviour of reinforced concrete structures. To that end, several nonlinear analyses have been performed with the software SAP2000®, considering the following plastic hinge models: (i) the model of FEMA-356 included in SAP2000®, and (ii) two additional models developed by some researchers by using empirical expressions calibrated with different experimental data. Simplified structures of two buildings have been used as examples.

The results obtained show that plastic hinges modelled with empirical expressions can be used by structural engineers to more precisely model the behaviour of structural elements in ordinary reinforced concrete buildings located in seismic areas, and to compare with the results offered by the models included in seismic building design codes.

1. Introduction

The prediction and simulation of the seismic behaviour of structures by using numerical models has been a field of growing interest in recent years, due to the importance of accurately knowing the effects and consequences caused by seismic actions on structures.

Seismic analysis can be performed by following different procedures, with differing degrees of accuracy achieved in the results. Nonlinear static analysis or pushover is one of the most frequently employed methods by structural engineers, due to its relative simplicity and the guidelines offered by the main seismic building design codes for its implementation. This analysis offers relevant information from the seismic point of view, such as the resistance and the deformation capacity of the structure. Pushover analysis can be implemented through different strategies, such as the modal pushover [1], the consecutive modal pushover [2], the upper bound pushover [3], the mass proportional pushover [4] and the adaptive pushover [5]. However, the increase in accuracy of all these methods is at the expense of the most attractive feature of conventional pushover analysis, namely its simplicity [6]. Therefore, conventional pushover analyses [7] have been implemented in the current study.

Adequate knowledge of the sectional behaviour of structural elements at yield and ultimate states is necessary in order to define the properties of the plastic hinges generated in the structure during nonlinear analysis. Thus, the yield moment M_y, the yield chord rotation θ_y and the ultimate chord rotation θ_u of the element's section are used to model the moment-chord rotation relations that define the behaviour of plastic hinges during the analysis.

In the seismic analysis of structures, the use of empirical expressions that reproduce the yield and ultimate states of a structural element's section is beneficial [8–10]. These expressions are accurate and efficient from the point of view of computation time, due to their relative simplicity and the fact that they are calibrated with experimental tests.

The main objective of the present work is the evaluation of the influence of the type of plastic hinge considered in the nonlinear behaviour of structures. To do so, several pushover analyses have

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Notation

a	confinement effectiveness factor
a_{cy}	zero-one variable for the type of loading (0 for monotonic loading, 1 for cyclic loading)
a_g	design ground acceleration on type A ground, defined in EC-8
a_{sl}	zero-one variable for slip (0 if slip of longitudinal bars from the anchorage is not physically possible, 1 if it is)
a_{st}	coefficient for the type of steel (0.0185 for hot-rolled or heat-treated steel, 0.0115 for cold-worked steel)
a_v	zero-one variable for diagonal cracking before flexural yielding of the end section
$a_{w,r}$	zero-one variable for rectangular walls (1 for rectangular walls, 0 for beams and columns)
$a_{w,nr}$	zero-one variable for non-rectangular sections (1 for T-, H-, U- or hollow rectangular sections; 0 for rectangular sections)
A_{sh}	area of lateral reinforcement
b	width of rectangular cross-section
d	distance from extreme compression fibre to centroid of tension reinforcement
d'	distance from extreme compression fibre to centroid of compression reinforcement
d_t	target displacement of the structure
E_c	modulus of elasticity of concrete
E_s	modulus of elasticity of reinforcement
f_c	compressive strength of unconfined concrete based on standard cylinder test
f_y	yield strength of tension reinforcement
f_y'	yield strength of compression reinforcement
f_{yh}	yield strength of lateral reinforcement
f_{yv}	yield strength of web longitudinal reinforcement
F_b	seismic base shear force
F_i	lateral force applied in the *i*-storey
g	acceleration of gravity
$G_{k,j}$	characteristic permanent action
h	height of rectangular cross-section
h_i	height from the base to *i*-storey
h_j	height from the base to *j*-storey
k	parameter with values depending on the fundamental mode T
L_s	shear span of member (= M/V at the end of the member)
m_i	mass of the *i*-storey
m_j	mass of the *j*-storey
M	bending moment
M_y	yield moment
N	axial force
$Q_{k,i}$	characteristic variable action
s_h	spacing of lateral reinforcement
s_i	displacement of the mass m_i in the fundamental mode shape
S_a	spectral acceleration
S_d	spectral displacement
V	shear force
z	internal lever arm
δ	control displacement, located at the centre of mass of the top storey of the structure
δ'	$=d'/d$
θ_y	yield chord rotation
θ_u	ultimate chord rotation
v	normalised axial load, N/bhf_c
ξ_y	neutral axis depth at yielding, normalised to d
$\psi_{E,i}$	combination coefficient for a variable action *i*, to be used when determining the effects of the design seismic action
ρ	tension reinforcement ratio, determined as ratio of tension reinforcement area to bd
ρ'	compression reinforcement ratio, determined as ratio of compression reinforcement area to bd
ρ_d	diagonal reinforcement ratio in diagonally reinforced members, determined as ratio of area of reinforcement arranged along one diagonal to bd
ρ_h	lateral reinforcement ratio (= A_{sh}/bs_h)
ρ_v	ratio of web longitudinal reinforcement, uniformly distributed between tension and compression reinforcement, normalised to bd
ϕ_L	diameter of tension reinforcement bars
ϕ_y	yield curvature of the cross-section
ω_1	total mechanical reinforcement ratio of tension and web longitudinal bars [= $(\rho f_y + \rho_v f_{yv})/f_c$]
ω_2	mechanical reinforcement ratio of compression reinforcement [= $\rho' f_y'/f_c$]

been implemented in two reinforced concrete structures, considering the following types of plastic hinges:

(i) Plastic hinges modelled from FEMA-356 [11], included by default in the software SAP2000® [12],
(ii) plastic hinges defined with the empirical expressions available in [9,10], and
(iii) plastic hinges modelled with the expressions developed by the authors [13,14].

In order to define the properties of the plastic hinges considered, the moment-chord rotation relations of the sections are obtained with the aforementioned methods. With the aim of considering the influence of the axial force N in the value of the yield moment M_y, some yielding curves N-M_y are defined for the columns of the structures.

In pushover analysis, it is important to study the global yielding and collapse points of the structure, which offer information about the ductility. Thus, the control displacement δ, the seismic base shear force F_b and the spectral acceleration S_a corresponding to those points are obtained. Additionally, the capacity curves F_b - δ of the structures are obtained.

Finally, the N2 method [15] proposed in EC-8 is implemented for two structures. Some ground acceleration values a_g are considered in order to study the influence of this parameter in the differences obtained with the different types of plastic hinges. Nonlinear time history analyses are performed to contrast with the results obtained using pushover analyses.

2. Plastic hinges models and analysis methodology

2.1. Equations for the sectional behaviour

Several expressions are suitable to reproduce the yielding and ultimate states of reinforced concrete sections from their geometry, reinforcement distribution and the mechanical properties of materials. In this line, Panagiotakos and Fardis [8] proposed several expressions to obtain the yield moment M_y, the yield chord rotation θ_y and the ultimate chord rotation θ_u. These expressions were calibrated with a database of more than 1000 experimental tests corresponding to beams, columns and shear walls. Later, Biskinis and Fardis [9,10] modified these expressions by calibrating them using an experimental database that included retrofitted elements.