Engineering Structures 156 (2018) 161–174

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Effect of yield penetration on column plastic hinge length

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ARTICLE INFO

Keywords:
Shear span
Bond
Yield-penetration
Plastic hinge length
Disturbed region

ABSTRACT

The required confined zone in critical regions of columns and piers undergoing lateral sway during earthquakes is related to the plastic hinge length where inelastic deformation and damage develops. The exact definition of the plastic hinge length stumbles upon several uncertainties, the most critical being that the extent of the inelastic region evolves and spreads with the intensity of lateral displacements. Design codes quantify a reference value for the plastic hinge length, through calibrated empirical relationships that account primarily for the length of the shear span and the diameter of primary reinforcing bars. The latter term reflects the effects of bar yielding penetration in the support of columns. Here a consistent definition of plastic hinge length is pursued analytically with reference to the actual strain state of the reinforcement. Strain penetration extending bilaterally on the reinforcing bars from the critical section towards the column shear span and towards the bar anchorage is evaluated. Considering that bar yielding is synonymous to degradation of interfacial bond between bar and concrete over the yielded area, the field equations of bond are solved explicitly along the column primary reinforcement over the shear span, following the process of gradual crack formation along the member. Boundary effects and important design variables are considered, such as the shear span aspect ratio and the stress-resultants (axial load and flexural moment) carried by the column. Using this solution, the parametric sensitivities of the plastic hinge length are illustrated and compared with other alternatives that have been obtained through experimental calibration. Analytical estimations are also compared with experimental evidence from a number of column specimens tested under axial load and reversed cyclic lateral drift histories reported in the literature.

1. Introduction

The plastic hinge length is used in reinforced concrete (RC) seismic detailing to determine the region where additional confinement requirements apply, but also in performance based seismic design and assessment in order to quantify the deformation capacity of RC columns. It has been studied, quantified and calibrated against tests on isolated column specimens. In the typical test, a cantilever column fixed at the base and carrying a constant axial load is driven to a reversed cyclic lateral load displacement history at the top. Deformation capacity of such members is usually described by the chord rotation that may be sustained by the member prior to loss of its lateral load strength. Contributing to the rotation are the flexural curvature that occurs along the length of the member, as well as the lumped rotation at the critical section resulting from inelastic strain penetration into the support (e.g. footing) as well as inside the shear span. This share of deformation is attributed to reinforcement pullout due to the incompatible length change between the bar and the surrounding concrete.

In columns that do not fail by web crushing, pullout rotation increases gradually with imposed drift, claiming a predominant share of the members' deformation capacity near the ultimate limit state. Column deformation capacity at yielding and ultimate may be computed using a variety of models [1–7]. A stick model is a common point of reference to this purpose: The length of the cantilever L_s corresponds to the shear span of an actual frame member under lateral sway (Fig. 1a); the aspect ratio of the member L_s/h, where h is the cross section depth, quantifies the intensity of shear force demand in the member. Inelastic activity is assumed to occur within an equivalent "plastic hinge length", ℓ_{pl}, whereas the segment of the member outside ℓ_{pl} is assumed to behave elastically. Displacements are calculated from flexural curvatures assuming the curvature distributions of Fig. 1(b,c), which correspond to development of yielding ϕ_y and post-yielding ϕ_u flexural strengths at the support. The plastic rotation developing in the hinge due to flexure is $\theta_{pl}{}^{f} = (\phi_u - \phi_y)\cdot \ell_{pl}$; similarly, the plastic rotation owing to bar pullout from the support is $\theta_{pl}{}^{slip} = \theta_u{}^{slip} - \theta_y{}^{slip}$ (Fig. 1d); the total plastic rotation is $\theta_{pl} = \theta_{pl}{}^{f} + \theta_{pl}{}^{slip}$. The

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https://doi.org/10.1016/j.engstruct.2017.11.003
Received 30 December 2016; Received in revised form 25 September 2017; Accepted 6 November 2017
Available online 20 November 2017
0141-0296/

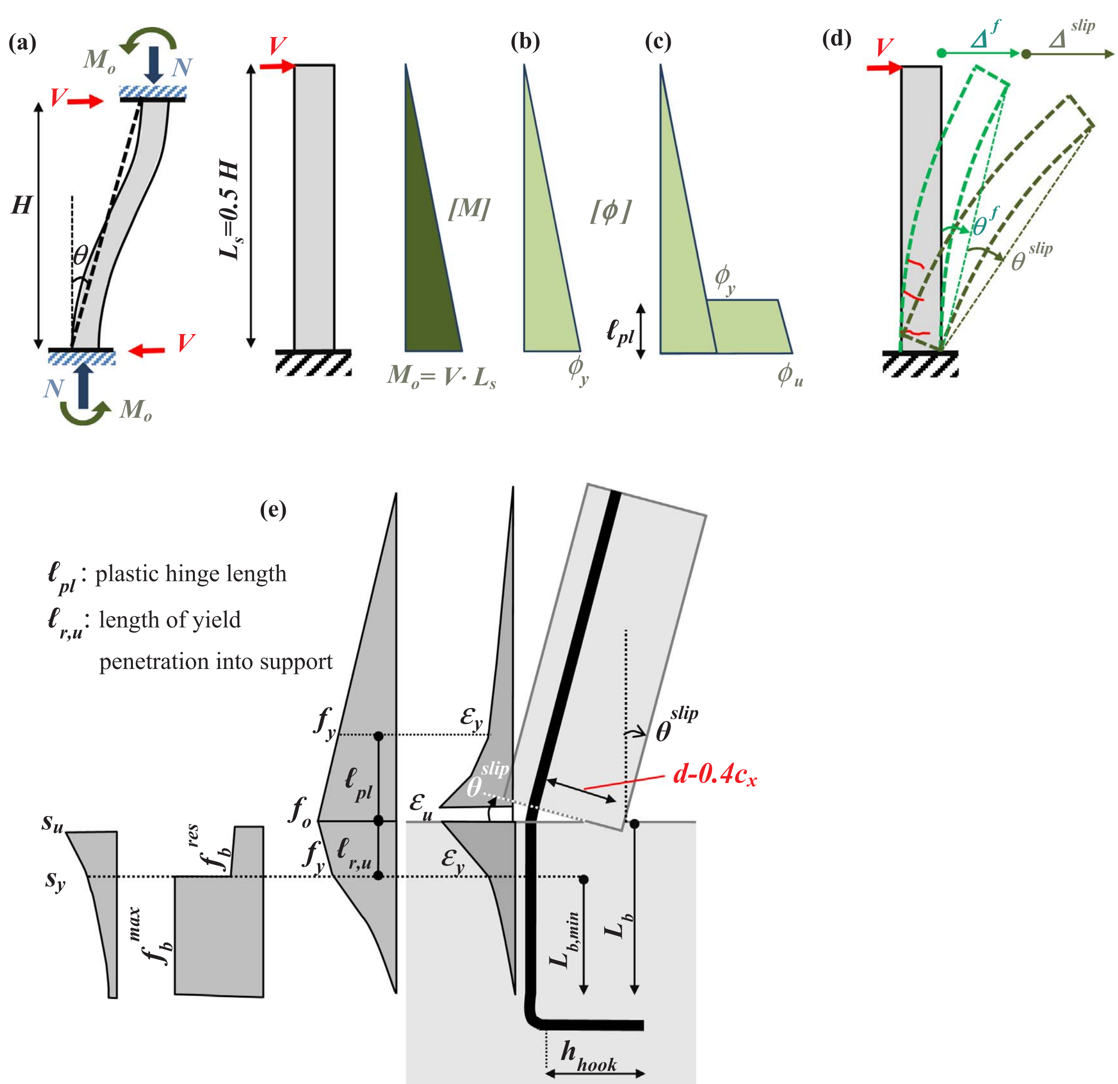

Fig. 1. (a) The stick model for a column under lateral sway. (b)–(c) Distributions of curvature along the column shear span at yielding moment M_y and at flexural strength M_u attained at fixed support ($M_u > M_y$) respectively. (d) Drift components from curvature along shear span (θ^f, Δ^f) and from anchorage slip (θ^{slip}, Δ^{slip}). (e) Bar state of stress/strain (f, ε) along shear span and anchorage of a cantilever column under horizontal loading at the tip. [Note: the bar bond/slip state (f_b, s) is illustrated only for the anchorage.]

corresponding terms are (Fig. 1e) (x is the length counting from the support to the tip of the cantilever column under study):

$$\theta_y^{slip} = \frac{s_y}{(d-0.4c_x)}|_{x=0};\ \theta_u^{slip} = \frac{s_u}{(d-0.4c_x)}|_{x=0};\ \ s_y \approx \varepsilon_y L_{b,min}/2;\ s_u \approx s_y + 0.5\cdot(\varepsilon_u + \varepsilon_y)\cdot \ell_{r,u};\ L_{b,min} = D_b\cdot f_y/(4 f_b^{max});\ \ell_{r,u} = L_b - L_{b,min} \tag{1}$$

where c_x is the depth of compression zone at the critical cross section (here it is assumed to remain constant after yielding) and L_b the total available anchorage length, whereas $L_{b,\min}$ is the minimum required anchorage length to yield a typical bar (diameter: D_b), at a yield stress f_y, considering a uniform bond stress equal to the bond strength of f_b^{max}. Rotation of the critical cross section occurs about the centroid of the compression zone (located at a distance $0.4c_x$ from the extreme compressed fiber based on the equivalent uniform stress block [8]). Parameters s_y and s_u are values of reinforcement pullout slip from the support anchorage at yielding and ultimate (Fig. 1e). Term $\ell_{r,u}$ represents the maximum sustainable penetration of yielding into the anchorage (Fig. 1e); the maximum reinforcement strain, ε_u, that can be supported by the reinforcement at critical cross section (i.e. support) may be estimated assuming that at the extreme, when the anchorage attains its ultimate development capacity the strain distribution along the anchored length is bilinear: $\varepsilon_u = \varepsilon_y + 4(L_b - L_{b,\min})f_b^{res}/(D_b E_{sh})$, where E_{sh} is the hardening modulus of steel and f_b^{res} is the residual bond strength due to cover splitting/delamination. The corresponding maximum and yield flexural curvatures are defined as: $\phi_u = \varepsilon_u /(d - c_x)$ and $\phi_y = \varepsilon_y /(d - c_x)$, whereas the total plastic rotation capacity, θ_{pl}, that may be sustained by the member may be estimated through reverse engineering as [9]:

$$\theta_{pl}^{slip} \approx 0.5\cdot(\phi_u - \phi_y)\cdot \ell_{r,u};\ \theta_{pl}^{f} = (\phi_u - \phi_y)\cdot \underbrace{\left(1 - \frac{M_y}{M_u}\right)}_{a}\cdot L_s \ \Rightarrow\ \theta_{pl} = (\phi_u - \phi_y)\cdot(\underbrace{0.5\cdot\ell_{r,u}}_{(i)} + \underbrace{a\cdot L_s}_{(ii)}) \tag{2a}$$

where in Eq. (2a) index (i) denotes pullout from support and (ii) flexure in the shear span; term α is the strain-hardening ratio of the reinforcement, $a = 1 - M_y/M_u$, defined from cross section analysis at ultimate moment given a simplified stress – strain law for the hardening branch of steel. Introducing the concept of the plastic hinge length, ℓ_{pl}, the plastic rotation capacity from Eq. (2a) is written as:

$$\theta_{pl} \approx (\phi_u - \phi_y)\cdot \ell_{pl} = \phi_{pl}\cdot \ell_{pl};\ \phi_{pl} = \phi_u - \phi_y;\ \ell_{pl} = 0.5\cdot\ell_{r,u} + \alpha\cdot L_s \tag{2b}$$

Empirical equations for the plastic hinge which have prevailed in