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Effect of axial force-bending moment interaction on stochastic nonzero mean seismic response of reinforced concrete frames

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ABSTRACT

Inelastic seismic analysis of buildings should consider the interaction of resisting axial force and bending moment in the columns, second order effects apart. Many fiber-based models are available but unsuitable for stochastic analysis, except Monte Carlo simulation. In contrast, a lumped plasticity frame model based on Bouc-Wen hysteresis, as recently extended to introduce interaction in a simple fashion, is straightforward to implement within stochastic equivalent linearization. Herein the interaction effect on the nonzero mean response is discussed. The model parameters are tuned for engineering structural analysis. Application is to eight reinforced concrete frames under gravity load and horizontal seismic excitation. The interstory drift appears to be almost insensitive to interaction. The rotation and energy ductility demands may change significantly, not only in the columns but also in the beams. All in all, increase prevails on decrease; the interaction effect is negative. For instance, decrease in the 95th percentile of rotation ductility demand is at most 10% or, in very few cases, 30%, whereas increase is up to 60% in most frames, and even two and three times in two frames. The bending moment statistics may change as well. Mean value is affected more than variance. Results are consistent with established outcome on nonzero mean random vibration. The interaction effect is marked on the outer members at bottom stories, tall frames, and soft ground. The lumped plasticity model seems to be suitable for practical structural analysis.

1. Introduction

As is well known, the resisting axial force and bending moment of a member cross-section are coupled according to the interaction diagram, second order effects apart. The influence of axial force on capacity, in terms of strength as well as ductility, is crucial to seismic performance of a column. In fact, any modern design code limits the normalized axial compression. There may be some influence also on seismic inelastic demand. Different approaches exist to analyze the flexural response depending on the axial force [1]. Referring to lumped plasticity models [2], one proposal based on multi-linear constitutive relationship dates to 70s [3]. Currently, fiber-based models are refined enough to combine the interaction of axial force and bending moment (PM interaction; acronyms are listed in Appendix A) with shear [4] and torsion [5] as well. Unfortunately, these models are very difficult, if not impossible to implement for stochastic analysis [6,7]. Their use is restricted to Monte Carlo simulation [8], conceptually simple but still too much time consuming in engineering practice.

In contrast, lumped plasticity models are poorer and have several shortcomings [9]. However, most importantly here, they are suitable for stochastic analysis. The frame model by Baber and Wen [10,11] in particular has been reconsidered recently to introduce PM interaction in a simple fashion [12], using the differential equation by Bouc [13] and Wen [14] formerly extended for asymmetric hysteresis [15]. Implementation within the ordinary stationary Gaussian nonzero mean stochastic equivalent linearization (SL) method is straightforward [12]. Simplicity and effectiveness of such frame model are deemed to be in line with the SL method, that makes it feasible seismic analysis of actual hysteretic structures [16–20] at the cost of inherent inaccuracy [21–24]. Within this context, a piecewise linear interaction of the biaxial bending moments has long been formulated following a general multivariate approach, which in principle can be applied also to PM, shear, and torsion interaction [25]. However, as far as the author knows, any implementation is missing, in contrast to continuing development of the SL method [26–36].

The preceding study on the model formulation and validation [12] is here expanded towards engineering application. First, the parameters of the hysteresis model provided with PM interaction, as well as asymmetry, are tuned for practical structural analysis. Second, the interaction effect on the nonzero mean stochastic response is discussed. Third, seismic analysis of eight reinforced concrete (RC) framed structures with different number of stories, ductility class, and ground type,

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is carried out. These frames are relatively squat. Moreover, column yielding is unlikely because the frame design complies with the weak-beam strong-column principle. Therefore, the model is here appraised with the interaction effect not being unduly amplified, as another step from the preceding study in which somewhat artificial results were compared with Monte Carlo simulation.

2. Frame model with PM interaction

As is detailed elsewhere [10–12], planar framed structures are considered. The members are modeled one-to-one as massless beam finite elements with zero-length flexural rotational springs at the ends. The axial, flexural, and shear behavior of the beam element is linearly elastic; plasticity is lumped in the terminal hysteretic springs. Any failure mode different from flexural yielding at the member ends is not modeled; it should be prevented by the frame design, i.e. by following relevant capacity design rules. Nevertheless, according to SL analysis the structural response, including the stress resultants and yielding itself, is random. Limited to flexural yielding, the springs should correspond to every potential critical region and be permanent in a stationary analysis. This feature contrasts with deterministic transient analysis, in which each spring is inserted as actual yielding occurs, and it may become inactive later [37].

Horizontal seismic inertial force and concurrent gravity load is considered. The former consists of filtered Gaussian stationary white noises at the frame joints, where the mass is assumed to be lumped. The gravity load is deterministic; it may include forces at the frame joints as well as weight distributed along a beam finite element.

Analytic formulation includes: (i) static and dynamic equilibrium equations of the frame joints; (ii) equality of the bending moments at the member ends and in the springs; and (iii) constitutive equations of the springs. Unlike pioneering study on the topic [10,11], the constitutive moment-rotation relationship of a spring follows here the Bouc-Wen model extended to incorporate asymmetry [15] and, most importantly, PM interaction [12]. This peculiar aspect is summarized next.

2.1. Extended Bouc-Wen model

The behavior model in terms of reacting bending moment M and flexural rotation θ of a spring is here formulated as follows, a little bit simpler than previously

$$M = \alpha A\theta + (1-\alpha)z \tag{1}$$

$$\dot{z} = \dot{\theta}\{Ay^n(P) - |z|^n[\gamma + \beta\mathrm{sgn}(z\dot{\theta}) + \delta\mathrm{sgn}z]\} \tag{2}$$

α is a parameter to emphasize the linear component or the hysteretic one, in parallel with each other, related to the post-yielding hardening ratio. z is an auxiliary variable to formulate stationary hysteresis; it may be seen as the hysteretic part of bending moment. A, n, γ and β are parameters of the original Bouc-Wen model. They are difficult to interpret strictly, which requires normalization and definition of mechanical quantities (e.g. the yielding strength) for a smooth behavior [38]. In a few words, A is related to tangent stiffness and strength as well; note that it appears in both Eqs. (1) and (2). n governs smoothness of yielding. γ dictates softening ($\gamma > 0$) or hardening ($\gamma < 0$) behavior. β introduces hysteretic behavior by making the tangent stiffness at loading ($z\dot{\theta} > 0$) different from that at unloading ($z\dot{\theta} < 0$). What is more, δ is a parameter from a former study to make the original model asymmetric [15]. Most importantly here, $y(P)$ is a function of axial force that introduces PM interaction [12]. In detail, it is reasonable to identify nominal yielding points as the intersections between the tangent at origin and oblique asymptotes of the smooth moment-rotation relationship (Fig. 1). Then the positive and negative yielding moments are obtained as

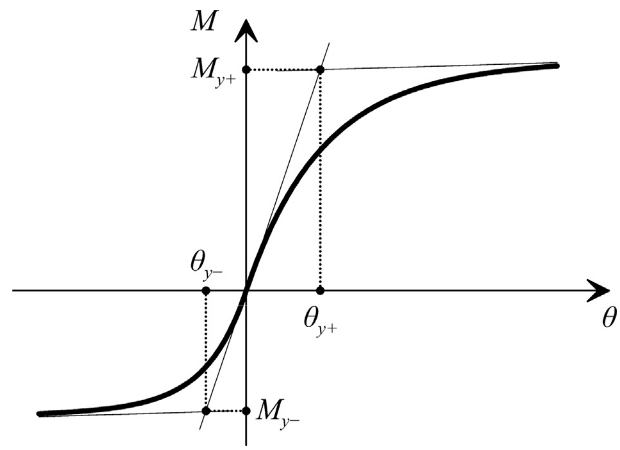

Fig. 1. Nominal yielding points of smooth asymmetric Bouc-Wen behavior.

$$M_{y+},\ |M_{y-}| = \left(\frac{A}{\gamma + \beta \pm \delta}\right)^{1/n}[\alpha y^{1-n}(P) + (1-\alpha)y(P)] \tag{3}$$

Setting $y(P) \equiv 1$ gives the previous model without PM interaction, symmetric ($\delta = 0$, implying $M_{y+} = |M_{y-}|$) or asymmetric ($\delta \neq 0$, the sign of δ dictating the stronger between positive and negative resistance). Instead, the following parabola has been proposed [12]

$$y(P) = 1-\left(\frac{2P-P_{\max}-P_{\min}}{P_{\max}-P_{\min}}\right)^2 \quad P_{\min} \leqslant P \leqslant P_{\max} \tag{4}$$

$P_{\min}$ and $P_{\max}$ are the extreme resisting axial forces at tension and compression failure of the member cross-section, respectively. It is noteworthy that $y(P)$ is dimensionless and bounded by zero and one. It merely dictates the shape of the PM interaction diagram, shown in the next subsection, while the parameters of the former model without PM interaction govern the dimensional flexural strength. Examples of the moment-rotation relationship are shown in Fig. 2.

Importantly, the axial force is assumed to depend linearly on translation of the frame joints. Crushing and tension failure from axial force cannot be captured. Second order effects are neglected as well. Clearly, the proposed model is simple and conceived for engineering use. Additional information and discussion can be found elsewhere [12].

2.2. Parameter tuning

Since hysteretic loops cannot be formulated as an explicit function, the role of each parameter of the Bouc-Wen model and its extensions has been studied mostly using numerical simulation, which however may give incomplete if not incorrect results [39]. Recently, optimum values of the parameters have been identified by the least squares [40–44], bootstrap filtering [45], differential evolution [46], genetic algorithms [47–49], and time-frequency analysis [50]. Unfortunately, any optimization method requires target hysteretic behavior from experimental test, which hardly ever is available for all members of the framed structure to analyze. The parameter values of the Bouc-Wen model extended for PM interaction and asymmetry are tuned here based on phenomenological mechanical quantities, such as the member strength and stiffness. Simple formulas are derived to be used in practical engineering analysis of framed structures.

Eq. (4) implies parabolic approximation of the PM interaction diagram. Strictly, this applies to the hysteretic component in the spring, i.e. the auxiliary variable z in Eq. (1). If the resisting bending moment is the intersection shown in Fig. 1, the interaction diagram normalized by the first factor in Eq. (3) appears as in Fig. 3. The shape is nearly parabolic only if the exponent n is small; how much small it should be, it depends on the hardening parameter α. Being $\alpha = 0.001$ (Fig. 3(a)),