COLLAPSE SIMULATION OF RC COLUMNS UNDER BIAXIAL CYCLIC LOADING

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ABSTRACT

Full-blown performance-based seismic design and assessment require multiple nonlinear dynamic analyses of 3D models. Collapse simulation requires the employed response models to be robust up to extreme response levels. For RC columns, the state-of-the-art in the field relies on phenomenological models calibrated versus experiments, whose robustness, computational cost and capability of describing member collapse for use within complex/large building models is unparalleled. These models, however, miss one possibly important aspect: the coupling between the responses in orthogonal planes. This work reports on ongoing research to develop a coupled phenomenological model for RC columns. Preliminary results from a multiple stripe analysis on a test building using an initial, basic implementation of the coupled model highlight a qualitative trend towards higher rates of collapse compared to uncoupled 3D models.

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Collapse simulation of RC columns under biaxial cyclic loading

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Full-blown performance-based seismic design and assessment require multiple nonlinear dynamic analyses of 3D models. Collapse simulation requires the employed response models to be robust up to extreme response levels. For RC columns, the state-of-the-art in the field relies on phenomenological models calibrated versus experiments, whose robustness, computational cost and capability of describing member collapse for use within complex/large building models is unparalleled. These models, however, miss one possibly important aspect: the coupling between the responses in orthogonal planes. This work reports on ongoing research to develop a coupled phenomenological model for RC columns. Preliminary results from a multiple stripe analysis on a test building using an initial, basic implementation of the coupled model highlight a qualitative trend towards higher rates of collapse compared to uncoupled 3D models.

Introduction

Performance-based seismic design and assessment relies on accurate analysis models. Additional refinement and the associated effort is justified by the goal, which is that of evaluating explicitly performance, rather than applying deemed-to-satisfy rules as in conventional prescriptive design. For the same reason it is also contradictory to talk about performance-based design or assessment, without proper, explicit, consideration of the many uncertainties involved. An extreme interpretation of this statement is that performance-based engineering is either probabilistic, or it is not performance-based [1]. The higher analysis cost associated with probabilistic methods in conjunction with nonlinear analysis can be justified only for important projects, and indeed tall buildings are the main realm of application [2,3]. Another case where the higher cost is justified is for (economically relevant) existing buildings, where analysis simplifications usually adopted in design cannot be exploited due to members with deteriorated or insufficient capacity and the consequences of a misjudgment on safety are high, possibly

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discriminating between the need for intervention or the possibility of leaving the building as is, vulnerable to seismic risks.

In all these cases, multiple nonlinear analysis of 3D models are required. Computational robustness, and the capability of describing the entire range or response up to collapse are a must. For this reason, in the last decade, phenomenological response models, e.g., piece-wise linear moment-rotation laws for plastic hinges, have become the de facto standard for collapse risk assessment, even though it is well known [4] that their performance at lower response levels is not on par with mechanical models such as fiber-sections [5]. Strengths and weaknesses of the two classes of models are complementary. Mechanical models [5] account for coupling between moments in orthogonal planes of bending, as well as with axial force; however, they fail to describe correctly member response close to collapse. On the other hand, computationally robust phenomenological models in widespread use [6] give a better prediction of collapse, but fail to capture coupling of bending and axial forces. Currently, there is a lack of experimental tests providing solid evidence that coupling of orthogonal bending moments with cyclic deterioration are of minor consequence in simulating the 3D seismic response of RC columns up to collapse. For this reason, two of the authors are currently conducting biaxial cyclic tests up to collapse on RC columns with other colleagues in Portugal. To complement these experimental efforts, whose details are described elsewhere, this paper reports initial steps and preliminary results in modeling efforts to capture flexural coupling effects in a computationally efficient phenomenological model. Additional efforts not shown here will extend the model to include cyclic deterioration, i.e., where flexural yielding in one direction leads to reduced flexural strength in the orthogonal direction.

**Response model and limitations**

A section model has been implemented in OpenSees [7] that adopts the concept of zero-force point put forward in [8] to model coupled, biaxial hysteretic response. For this study a preliminary version of the model has been used, with a bilinear backbone (positive stiffness branch to peak strength, followed by negative stiffness branch to maximum deformation at zero force) plus kinematic hardening. The full model uses a trilinear backbone along with energy-based strength and stiffness degradation, and peak-oriented pinching behavior [8]. Although these additional features are in development in OpenSees, the basic bilinear model is employed herein to demonstrate the basic effects of biaxial flexural coupling compared to the common approach of using two uncoupled uniaxial relationships to represent flexural response in 3D.

Figure 1a and b show the experimental force-displacement loops in two orthogonal planes from one of the tests conducted in Portugal mentioned earlier (blue). The test is carried out on a square column with the same backbone in both directions and elliptical load path with maximum orthogonal (E-W) displacement amplitude equal to 50% of that in the main (N-S) direction. The coupled model simulation is shown in red, alongside the uncoupled one in black (same backbone and hysteresis). The figure shows how this preliminary, overly simplified cyclic law captures the characteristic rounding of force-displacement cycles due to coupling, i.e., orthogonal unloading while displacement is still increasing in one direction. Nonetheless, as expected, the results are characterized by a significant over estimate of the energy dissipated per cycle because the response is bilinear with kinematic hardening.
Figure 1. Comparison of uncoupled (black) and coupled (red) models with actual test results on a RC column tested in biaxial flexure (a) and (b); Plan of the SPEAR test building (c); Coupled (red) and uncoupled (black) moment-rotation in the hinge at the base of the first floor column, marked in red in (c), reaching collapse first (at about 6% rotation) for motion 11 of stripe 6 (d); multiple-stripe analysis results e) and (f).

Case study and results of the analysis

The preliminary version of the biaxial hysteretic model has been used to describe columns in an OpenSees model of the SPEAR project three story test building (non-seismically designed older building with SCWB behavior [9]), whose plan is shown in Figure 1c. A multiple stripe analysis
with ten intensity levels and 20 bidirectional ground motions per stripe has been carried out. The records are from [10] and have been selected with the conditional spectrum approach to reflect seismicity in the Caltanissetta city in Sicily, Italy (conditional to $S_a(T_1=1s)$). Differences in dissipated energy due to coupling, shown already in Figure 1a and b, lead to different dynamic responses. Collapse is therefore reached in some cases with the uncoupled model, but not the coupled model (see Figure 1d). The overall multiple stripe analysis results are shown in Figure 1e and f, in the X and Y plan directions, respectively. Each panel shows the maximum roof drift ratio in the corresponding direction for both models and all intensity levels. Results for the uncoupled and coupled model are shown slightly below and above the intensity level, for clarity. Even though obtained with a very simplified initial version of the coupled model, the results show an increase in the collapse rate obtained with the coupled model.

Conclusions

Due to the basic bilinear, kinematic behavior of coupled hysteretic response, the preliminary results are not yet significant in quantitative terms, but show qualitative traits that justify continued model development. In particular, a slight increase in collapses, at the same level of intensity, is recorded in the (single) analyzed 3D building frame when using the coupled model, and even one collapse at a lower intensity. Experiments have shown that degradation is increased by orthogonal excursion; therefore, it is expected that the rates of collapse will be higher when the aspects of trilinear backbone, peak-oriented reloading, and cyclic strength deterioration are included in the OpenSees model. Whether this increase will be large enough to make a difference in risk analysis is the primary long term research question for this effort.

References