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Fostering Structural Earthquake Engineering on Early Years College Students through Field Damage Observations and Fiber-Based Simulations

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ABSTRACT

Because of the already crowded civil engineering curriculum and the amount of previous knowledge required, earthquake engineering topics are barely taught at the undergraduate level and is mostly reserved as an advance course in graduate school. In this article we show how we engaged fiber-based simulations along with field damage observations from the 2020 southwest Puerto Rico earthquake sequence to introduce early year college students from different academic backgrounds into structural earthquake engineering. It was found that fiber-based modeling provides a natural way of modeling civil structures and offer results that can be easily related with the expected/observed damages, making it an efficient tool to introduce key aspects of the structural seismic response and motivate early year college students to pursue further studies in this field.

Introduction

Due to its geographic location, Puerto Rico is prone to two of the most devastating natural hazards: hurricanes and earthquakes. Moreover, the resilience of its civil infrastructure is significantly affected by its exposure to harsh environmental conditions and severe climate changes. In September 2017 the island was struck by Category 4 Hurricane Maria causing massive damage to the infrastructure [1]. Puerto Rico has also a long history of destructive earthquakes. Historical records show that major earthquakes have struck Puerto Rico and the Virgin Islands in 1615, 1670, 1787, 1844, 1846, 1867, 1875, 1906, 1918, 1943 and 1946, with estimated moment magnitudes between 7.2 and 8.2 With the 1867 and 1918 earthquakes accompanied by destructive tsunamis [2]. Currently, the island is going through a seismic sequence that started with a M4.7 event on December 28, 2019 [3]. Since then, and until this manuscript is being written (September 2021), 43 earthquakes with magnitude 4.5 or larger have occurred, 15 of them of M5 or larger. In terms of the induced structural damage, the more significant events have been the M5.8 on January 6 and the M6.4 on January 7, that provoked the collapse of several soft-story single family dwellings and a 3-story operational reinforced concrete school, significant damage has been reported in other structures [4].

The NSF funded Resilient Infrastructure and Sustainability Education – Undergraduate Program (RISE-UP) was envisioned to provide the intellectual and practical academic space to generate case study research and turn them into hands-on solutions for real problems/projects, starting with the ones generated by the impact of Hurricanes Irma and Maria and now the ones arising from the on-going seismic sequence. The challenge with the seismic sequence was how to design the projects so that realistic and relevant solutions could be reached by undergraduate students for a problem, earthquake induced damage, that is complex in nature - as it involves the nonlinear degrading response of a

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system subjected to dynamic non-stationary excitations. Time was another constrain, we had six weeks of summer to complete the projects. The motivation on the students was high as the earthquake sequence was/is on-going, and the main shock induced damage to many structures, including houses from the students and university buildings itself. Based on this, it was decided to work with real case projects selected from the most documented failures that at the same time affected the students (and faculty) daily lives. The structures selected were a power plant in southern Puerto Rico that was damaged causing power outage, a reinforced concrete bridge pier on a main road near campus, a typical reinforced concrete school susceptible of short column failure and soft-story residential houses which were the type of structures most affected and unfortunately quite common in Puerto Rico [5]. Each structure was analyzed by a team composed of four undergraduate students with different academic background (architecture, civil engineering, electrical engineering, surveying). The objective was quite challenging: to develop a model of the structure, identify key features of the seismic response – including the failure mechanism, and propose a viable retrofit. This article focuses on the projects based on soft-story residential houses which were modeled using a fiber-based distributed plasticity approach.

Fiber-based vs hinge-based models

Studies to evaluate the overall seismic performance of buildings, including prediction of losses and other performance measures, as presented in FEMA P-58, Seismic Performance Assessment of Buildings [6] rely on the results from nonlinear dynamic (response history) analysis. In frame structures, the structural components are usually modeled using a hinge-based approach or a fiber-based approach [7]. In the hinge approach (Fig. 1 – left), the inelastic deformations are concentrated into rotational springs at the ends of a linear elastic element. A drawback of this approach for the purposes of this work (introducing early years undergraduate students to earthquake engineering) is that the definition of the moment-rotation laws (e.g., the Ibarra–Medina–Krawinkler deterioration models [8]) that control the deformations in the non-linear spring, demands a level of knowledge absent in our students. For example, it implies performing moment-curvature analyses and use statistical calibrated predictive equations (e.g. [9]) to set the parameters required to define the backbone curve and additional parameters to account for the cyclic deterioration of strength and stiffness. Conversely, in the fiber-based approach (Fig. 1 – right) the element section is modeled using unidirectional fibers with constitutive relationships (stress-strain curves) for each of material. For modeling a reinforced concrete element for example, we will have fibers representing the reinforcing steel, cover concrete (unconfined), and core concrete (confined). That is, the element section is modeled by modeling each of their constituent materials, which make it easier for sophomore/junior undergraduate students to visualize and faster to implement. Moreover, induced material strains which can be easily related with the level of expected/observed damages are directly extracted from the analyses results. In the hinge-based methods, the induced deformations are retrieved in the form of rotations – which require further knowledge and experience to be properly interpreted. In terms of the efficiency and accuracy of the different approaches, while hinge-based models are less computational demanding and more stable, fiber-based models have been found to provide a closer agreement with experimental results [10,11].

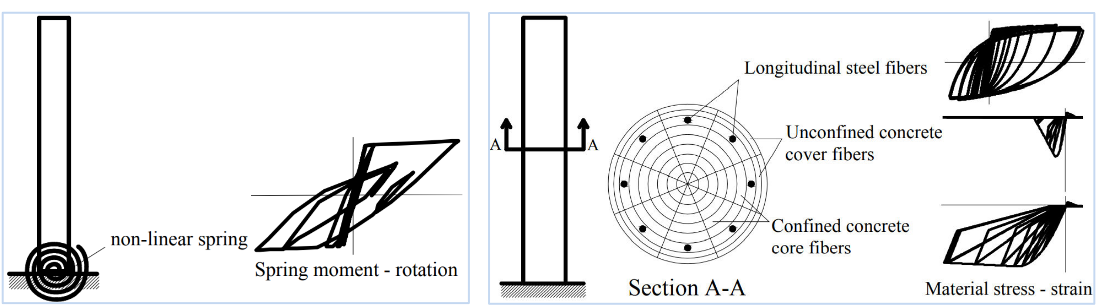

Figure 1. Left: lumped plasticity "hinge" model. Right: fiber-based distributed plasticity model.

Course/project structure

This was a 6-week summer course for early years undergraduate students from different academic backgrounds. None of the students had taken any design course (reinforced concrete or steel design) but all had approved engineering mechanics statics and some the mechanics of material course. The course was hands-on project-based, with only a brief lecture the first week. The structure of the course/project is next described in a week-by-week basis.

Week 1: The course started with a brief introduction to earthquake engineering, special emphasis was placed on steel and concrete stress-strain behavior as this was a key aspect for the development of the structural model. Other concepts were addressed as required along the execution of the project. This week the students were asked to research/"survey" the structure to be modeled (Fig. 2a,b) and develop blueprints and 3D CAD models (Fig. 2c).

Week 2: Started the development of the structural model (Fig 2d). While the most popular and flexible platform for fiber-based modeling is OpenSees [12], we decided to use SeismoStruct [13] because of the availability of a robust graphical user interface and default modeling options. The students were asked to assess and distribute the gravitational loads, load the model, and run a static gravitational analysis. The model was validated by comparing the estimated weight of the structure from hand calculations with the one calculated by adding the vertical reactions from all columns.

Weeks 3 and 4: The students incorporated the "non-structural" masonry walls into the model and performed a lateral load (pushover) analysis in both horizontal directions. They were asked to identify the displacements/drifts at which the structure reached different performance levels based on target material strains (first yield, serviceability, damage control) and compare the results between directions (Fig. 3).

Week 5: The students performed an eigenvalue analysis and a nonlinear time history analysis. From the eigenvalue analysis the students were asked to extract the 3 first modes and their natural periods. Due to time constrains, the time history analysis was performed with a single record (both horizontal components were applied simultaneously). The record was a spectrally matched to a typical ASCE-7 design spectrum for Puerto Rico (Fig. 4).

Week 6: Finally, based on the results obtained from the simulations, the students proposed a retrofitting strategy based on reinforced concrete jacketing of some of the columns at the first level. The retrofitting was implemented in the numerical model and the students were able to compare the expected behavior of the retrofitted structure against the model without retrofitting (Figs. 3 and 4). Each group presented their work at the end of this week.

Figure 2. (a) Damaged house after M5.8 earthquake, (b) collapsed house after M6.4 earthquake, (c) 3D CAD model by the students, (d) fiber-based numerical model in SeismoStruct.

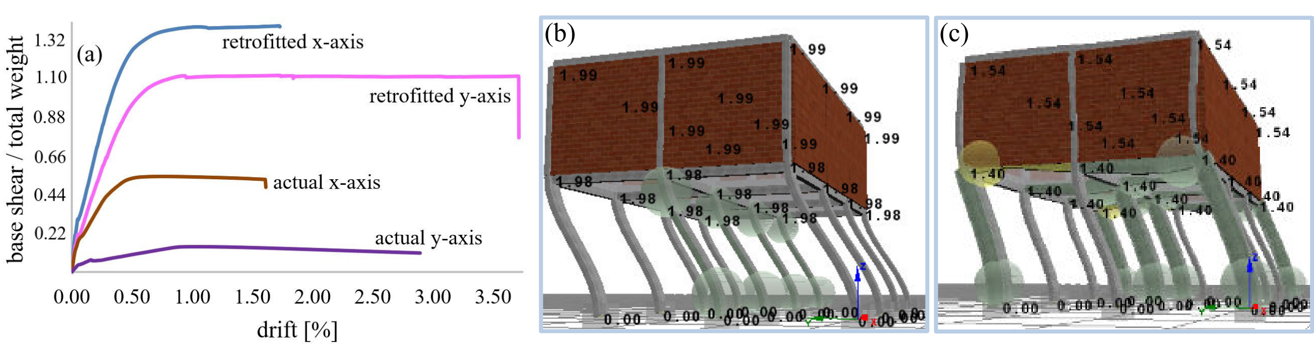

Figure 3. (a) Capacity curves from pushover analysis in both directions for the actual and retrofitted structure, (b) failure mechanism of the actual structure, (c) failure mechanism of the retrofitted structure

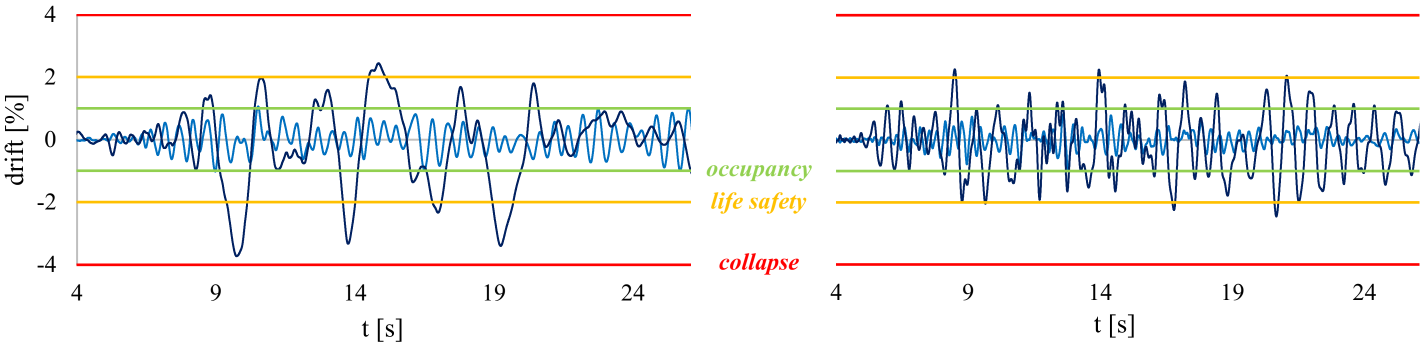

Figure 4. Maximum interstory drift from nonlinear time history analyses for the actual (left) and retrofitted (right) structures. Dark blue lines correspond to the weak axis (y) and light blue to the strong axis (x).

Results summary

The students were able to develop a fiber-based nonlinear structural model for a soft story reinforced concrete house. The students validated the model through hand calculations and comparisons with the actual behavior of the collapsed structure. The students were able to identify two critical aspects of the current informal construction practice on the island through the results obtained from the analyses performed: (1) the use of rather thin columns (6in*16in) oriented all on the same direction - resulting in an axis of the structure being significantly weaker and (2) the construction of masonry walls only on the second floor – resulting on a large stiffness contrast between the two floors and causing the first floor to absorb most of the inelastic deformations. Both issues were assessed from the pushover analyses results (Fig. 3) and further reinforced by the dynamic analyses and the actual structure collapse characteristics (Fig. 2b). The retrofitting scheme proposed and implemented in the numerical model by the students significantly improved the seismic behavior of the structure, not only by increasing stiffness and strength, but also reducing the differences in strength and stiffness between the two horizontal axis and between the two floors.

Conclusions

It was found that the combination of fiber-based simulations and field damage observations can be used as an expedient tool to introduce undergraduate students into nonlinear modeling and earthquake engineering. For undergraduate level experiences, fiber-based modeling requires less knowledge and experience than the more established hinge-based approach. Interpretation of the results is also easier as it provides material strains, which can be easily related to damage levels. The students were able to quickly develop their model and start getting results that allow them to easily assimilate key concepts on seismic response, like stiffness, strength, ductility capacity, inelastic demand, in-plan and vertical irregularities. At the end, the students were able to identify the main issues affecting the seismic behavior of the structure and implement a rational retrofitting scheme.

Finally, although constantly stressed out in the manuscript, this was a first modeling experience aimed to introduce and motivate undergraduate students into the field of earthquake engineering. Some advanced concepts critical in nonlinear analyses (like damping, strain concentrations, shear deformations, etc.) were not comprehensively addressed because of the limitations of time and required previous knowledge. Moreover, the models developed assumed that the foundation and beam-column joints were properly designed and built, which is unlikely to be the case as observed in the inspection of damaged structures after the main shock.

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