Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2025) 5 61-5 68

ECCOMAS
Proceedia

COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15-18 June 2025

NONLINEAR SEISMIC ANALYSIS OF RC STRUCTURES: INFLUENCE OF MATERIAL PROPERTIES ON HYSTERETIC DAMPING

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Abstract
Nonlinear Response History Analysis (NRHA) is the most accurate method to predict the building's response to a seismic action. Numerous factors and parameters influence its results. This article aims to understand how different material constitutive models affect the seismic response of a case study building. The case study building is a three-story reinforced concrete building designed for gravity loads only, representing the Italian building stock of the 1970s. The building is modeled in OpenSees using a distributed plasticity model with fiber sections at the integration points and different commonly used uniaxial constitutive laws are considered. For each case, nonlinear dynamic analyses were performed using 20 pairs of ground motion records selected for a 475-year return period. The results are compared to evaluate the influence of different material types on the hysteretic damping and overall response of the case-study building

Keywords: Reinforced concrete, Hysteretic Damping, Nonlinear Response History Analysis (NRHA), Distribuited plasticity model, fiber section, uniaxial constitutive laws

ISSN:2623-3347 © 2025 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2025.
doi: 10.7712/120125.12818.24954

1 INTRODUCTION

Damping in structural systems refers to the dissipation of energy from a vibrating system. Damping can be categorized into two types: hysteretic damping, associated with the energy loss within the material itself due to cyclic loading, and additional damping, which accounts for all other energy dissipation mechanisms not explicitly modeled. The most common approaches for modeling additional damping in structures, implemented in OpenSees software [1], are Rayleigh damping [2, 3] and modal damping [4, 5, 6]. In an "ideal" model where all dissipating phenomena are explicitly models, there is no need for additional damping.

Although hysteretic damping is a significant factor in seismic response, its quantification and representation are complex. In the case of reinforced concrete buildings, the focus of this paper, the dissipation mechanisms that can be taken into account are primarily due to the energy dissipation in the loading and unloading cycles of concrete and steel. Therefore, the selection of constitutive models for concrete and steel is very important. The objective of this paper is to compare how different material constitutive models influence the seismic response of a RC building.

2 CASE STUDY DESCRIPTION

A large number of Italian buildings constructed from reinforced concrete were built between the 1960s and 1970s [7]. These buildings were often designed without seismic prescription and/or according to outdated seismic codes. The building examined in this study was designed only gravity loads. This building has 3-story, which aligns with the observation that many existing non-compliant buildings [8]. The structure (see Figure 1) has a rectangular plan, with 4 main frames in the X-direction and 2 in the Y-direction. The beams are deep, and the columns have their strong axis aligned with the main frames, resulting in significantly greater lateral stiffness and resistance in the X-direction compared to the Y-direction.

Figure 1: 3D of case study building

The cross sections and reinforcement of the columns and beams were determined using the allowable stress design method prescribed by the Italian building code in use during the 1970s (DM 1974) [9]. The concrete has a characteristic cubic compressive strength of R_{ck} = 25 MPa, while steel grade Feb38K with a yield stress f_{yk} = 375 MPa.

3 NUMERICAL MODELS

Building model created using STKO software [10], a pre/post processor for OpenSees [11]. A distributed plasticity approach was used to model beams and columns [12], using the Beam-with-Hinges element [13]. This element employs a force-based formulation with Gauss-Radau integration, confining non-linear material behavior to localized plastic hinge regions with a defined length (L_{pl}). These regions are modeled using fiber sections [14, 15]. The remaining portion of the element with elastic sections, carefully calibrated to account for cracking effects (0.5EI for Beam and 0.8EI for Column). The plastic hinge length is calculated in a assumed equal to the section depth. In columns with rectangular sections, the average value between the two depths was used. The models incorporate P-Delta effects. Floor diaphragms are modeled using the MPconstraints "rigidDiaphragm" element. The model was made to have a Shear-Type behavior. The rigid diaphragm constraint restrains axial deformation in the beams, introducing spurious axial forces. To mitigate this issue, a ZeroLength element (or axial buffer element [16]) is employed. To investigate the influence of different material types on hysteretic damping, 4 concrete constitutive law and 2 steel constitutive law were used for the fiber sections. For concrete, Concrete01 (C01) [17], Concrete02 (C02) [17], Concrete04 with and w/o tension (C04) [18,19,20], and Concrete07 (C07) [21,22] were employed. The same properties were used for the concrete cover and confined zone, while Steel01 (S01) [23] and Steel02 (S02) [23] were used for steel. Table 1 presents the values of the constitutive models of the materials used. Figure 2 illustrates the constitutive law of the materials and the parameter values used.

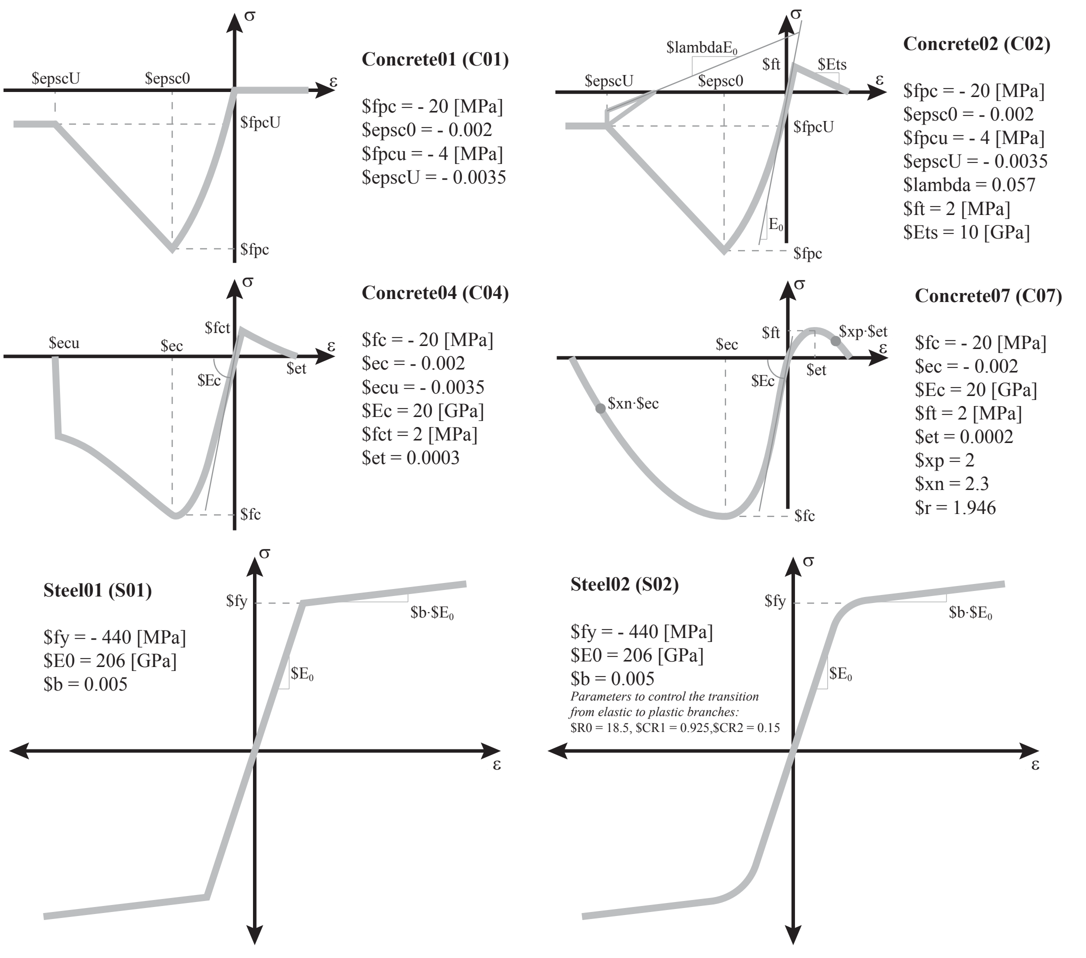

Figure 2: Constitutive law of fiber section

By combining the different concrete and steel constitutive laws, 10 models were defined, as shown in Table 2. Potential brittle failure in beam/column elements and beam-column joints and infills are not model.

	C01	C02	C04 w/o Tension	C04	C07
S01	**C01S01**	**C02S01**	**C04wtS01**	**C04S01**	**C07S01**
S02	**C01S02**	**C02S02**	**C04wtS02**	**C04S02**	**C07S02**

Table 1: Names of models with combination between different constituent laws

4 NONLINEAR RESPONSE HISTORY ANALYSIS

Ground motion records for the Non-linear Response History Analyses (NRHAs) were chosen based on L'Aquila, Italy with a 475-year return period. The records were sourced from the European Strong-motion Database (ESD) and the Engineering Strong-motion database (ESM). Twenty pairs of unscaled ground motion records were selected [24] for each building. The 20 analyses were conducted by neglecting any supplemental damping mechanisms and focusing only on the inherent hysteretic damping of the materials. The results of the NRHA analysis are presented in Figure 3, with the maximum displacement of the center of mass (RD) of the top floor [25] . These cases refer to analyses that did not converge, as indicated in Figure 3 with an unfilled marker.

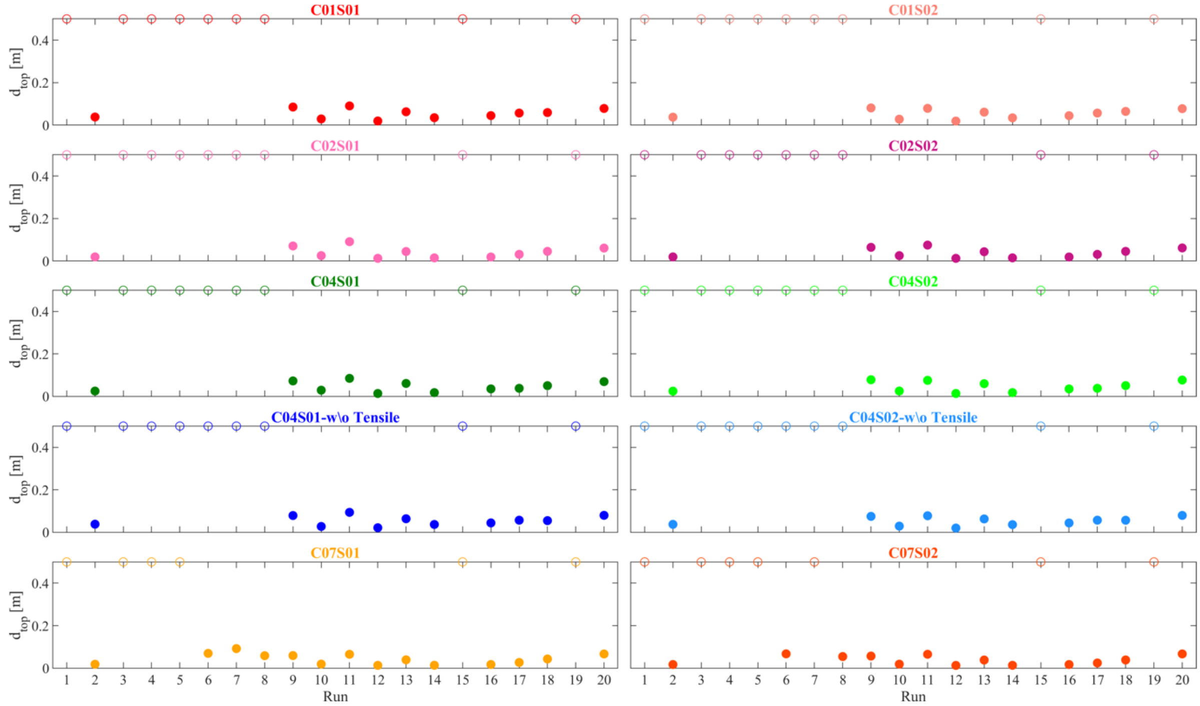

Figure 3: Results of NRHAs in terms of maximum RD in the X and Y directions (Red marker for X direction, Blue marker for Y direction, with filled markers indicating converged analyses and empty markers indicating non-converged analyses)

The results of the convergent analyses show differences in terms of maximum displacement in the two directions as the materials of the fiber sections vary. In general, it can be observed that the two types of steel, for the same concrete, give very close results. On the other hand, the variation of the constitutive law of the concrete has a more impact on the results but also on the convergence of the analyses

5 HYSTERETIC ENERGY

In the convergent NRHA analysis, hysteretic energy was determined by calculating the area enclosed by the hysteretic loops of each column. Then, these individual column energies were summed to obtain the total energy for the entire analysis. Figure 4 shows the results in terms of energy for the convergent analyses, as for the results in terms of maximum RD, differences are observed between the various materials used for the fibers in the sections. The differences tend to increase as the dissipated energy increases; in fact, in runs 9, 11, and 20, the differences are greater. Furthermore, these three analyses are among those that show the greatest maximum Roof Displacement.

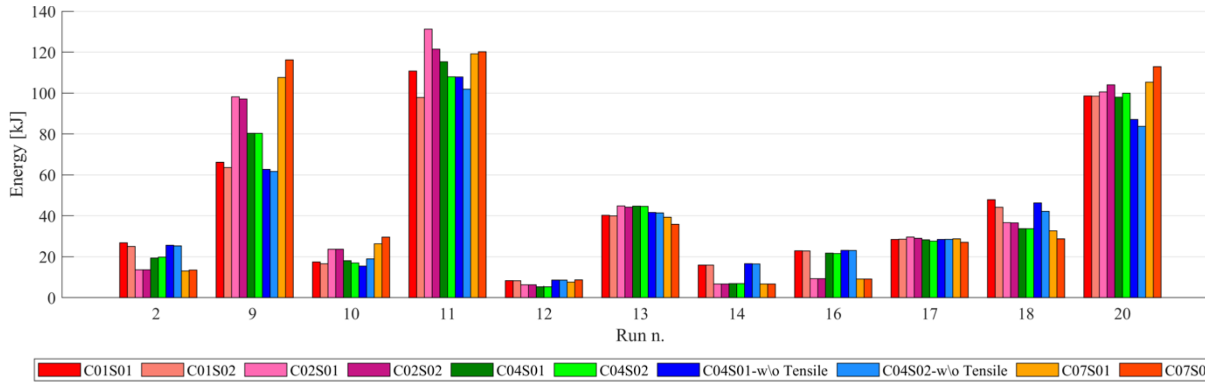

Figure 4: Results of NRHAs for all converged analysis in terms of Energy

In the first comparison that takes place between the two materials (Steel01, Steel02) used for steel fibers, it can be observed in Figure 5 how the differences in terms of energy between the use of the two materials are minimal. Instead, consistent differences are observed as the various concrete fiber laws.

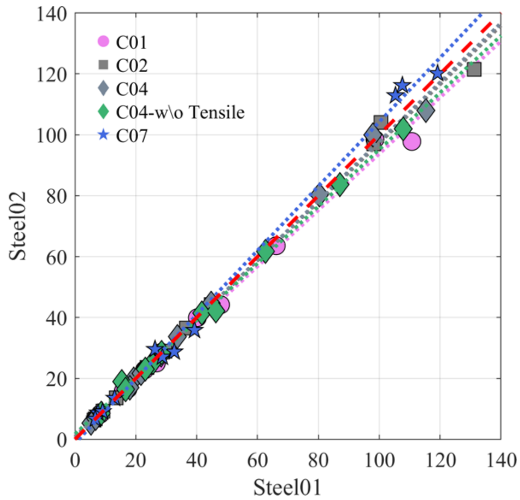

Figure 5: Comparison between Steel01 and Steel02 in terms of Energy

In Figure 6, the energy comparisons between the different concrete constitutive laws used for the fibers. Comparing C01 and C02 (Figure 6-a), where the only difference is in the tensile component of the constitutive law, different results in terms of dissipated energy are observed. The same applies to C04 (Figure 6 -b). The variations between C01 and C04 w/o tensile are minimal and nearly negligible (Figure 6 -c).

Comparing (Figure 6-d/e/f) instead the various concrete constitutive laws with tension (C02, C04, and C07), the largest differences in terms of dissipated energy are observed when comparing with C04 , which provides lower results than C02 (Figure 6-d) but higher results than C07 (Figure 6-f). Finally, comparing C02 and C07 (Figure 6-e), the differences are negligible. In summary, the greatest influence on dissipated energy is given by the different concrete laws; one of the reasons is that, compared to S01 and S02, the parameters in concrete are multiple, and the equations defining the constitutive laws are different from each other, leading to differences shape form and therefore in energy content.

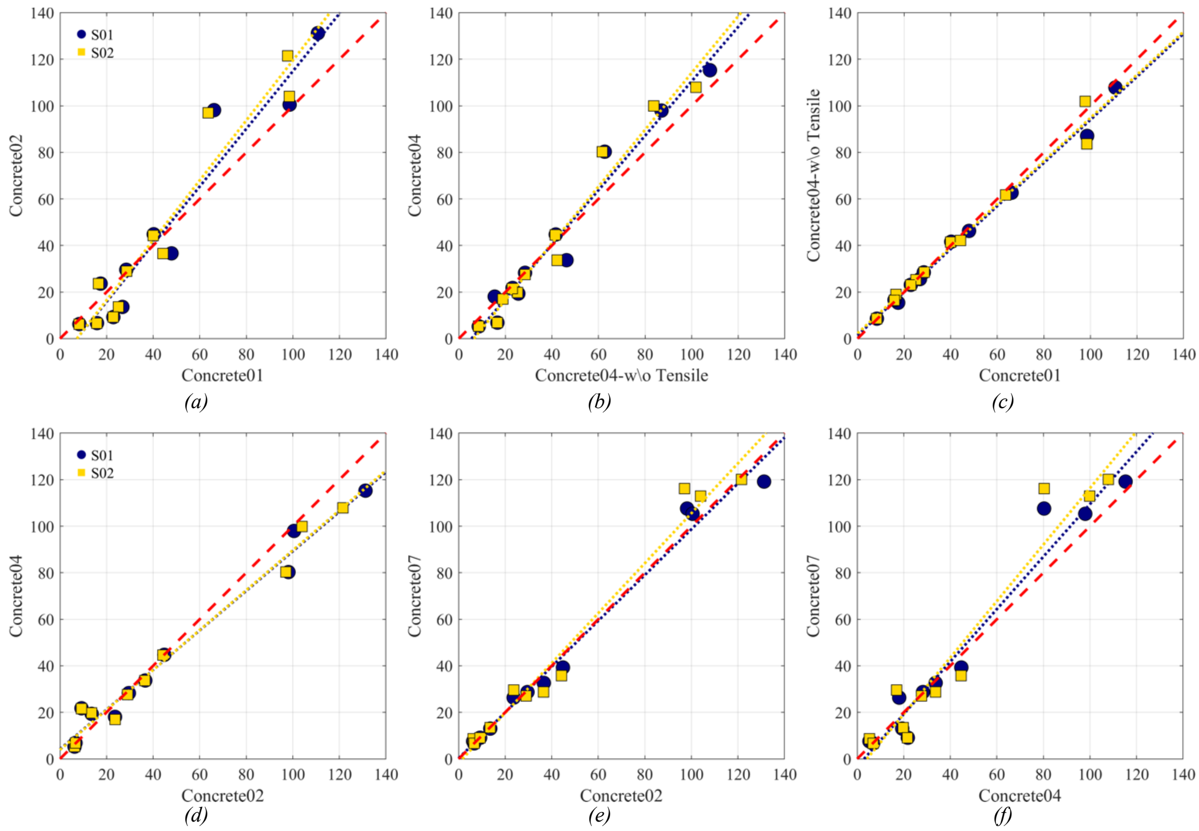

Figure 6: Comparison between different Concrete Law in terms of Energy

6 CONCLUSION

The aim of this article was to understand how different material constitutive models influence the seismic response, in terms of hysteretic damping energy, of a building under study. The case study building is a three-story reinforced concrete building, designed for gravity loads. The model was developed in OpenSees using a distributed plasticity model with fiber sections.

To investigate the influence of different material types on hysteretic damping, 4 concrete constitutive law (C01,C02,C04,C07) and 2 steel constitutive law (S01,S02) were used for the fiber sections. Twenty nonlinear dynamic analyses were performed. The results are compared to evaluate the influence of different material types on hysteretic damping and the global response of the building. In general, it can be observed, both for the max RD and for the hysteretic energy, that the two steel constitutive laws, with the same concrete, produce very similar results. On the other hand, variations in the concrete constitutive law lead to greater differences in the results, although they are still minimal. These differences observed when varying the concrete law used can be attributed to the constitutive laws where the parameters in concrete are multiple, and the equations defining the constitutive laws are different from each other, leading to differences in shape and therefore in energy content. This article aims to be only a starting point for a broader and more extensive study, extended to other structures and also considering other constitutive laws for concrete and steel.

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