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Identification of Limit Exceedance Points in a Reinforced Concrete Frame Under Pushdown Analysis Using OpenSeesPy

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Abstract. Progressive collapse is characterized by the propagation of local damage from an initial event, leading to the successive failure of structural elements and, eventually, the total or partial disproportionate collapse of the structure. Such damage can result from explosions, impacts, fires, earthquakes, construction errors, differential foundation settlements, exceptional snow loads, among other factors. Given the severity of these events, which cause material losses and, most importantly, pose risks to human life, research in this field has intensified. The analysis of progressive collapse is conducted through structural modeling using finite element software, with the pushdown method being widely employed. In this procedure, a column is removed from the structure, and a controlled displacement is applied at the removal point, while the corresponding force and displacement are recorded. In this study, the Python module OpenSeesPy will be used to assess the location of failure points where the steel exceeds a limit (initiation of plate formation) and the concrete exceeds a limit (crushing) in a reinforced concrete frame under pushdown analysis. The structural elements will be modeled as nonlinear beam-column elements using a layered approach (fiber section), which accounts for the distribution of stresses and strains across the cross-section. In this context, the aim of this paper is to evaluate a numerical model that will provide insight into the failure mechanism to which the structure is subjected after the pushdown analysis.

Keywords: Limit Exceedance, Frame Structures, Pushdown Analysis, Reinforced Concrete, OpenSeesPy

1 Introduction

Progressive collapse is an event with significant societal impact, as exemplified by the 2021 collapse of the Champlain Towers South condominium in Surfside, Florida. Analyses suggested that failure of deep beams at the pool deck level, directly linked to the perimeter columns of the structure, could have led to the columns' failure and ensued collapse of the eastern wing of the building [1]. Another notable case is the 2013 collapse of the Rana Plaza building in Bangladesh, attributed to improper construction [2]. In Brazil, the 2012 collapse of the Liberdade Building in Rio de Janeiro was triggered by improper renovations [3]. A further significant incident was the 2018 collapse of the Wilton Paes de Almeida Building in São Paulo, which occurred after a large fire [4]. A more recent case occurred on 4 January 2024, when an explosion in a building in Porto Alegre, likely caused by a gas leak on the third floor, resulted in the collapse of one floor and compromised the floor above it [5].

The scenario is assessed through nonlinear static pushdown analysis, which begins with the removal of critical members and subsequently investigates the complete behavior of the damaged structure. Using a displacement-control strategy, successive vertical displacement increments (Δ) are imposed at the joint of the removed column, and the corresponding reaction load is recorded. To visualize the structural behaviour, a code was developed to display the points where the material exceeds the adopted limit.

2 Methodology

Progressive collapse behaviour can be modelled using finite element software such as ABAQUS, Ansys LS-DYNA, DIANA, and OpenSees. The Python module OpenSeesPy, a Python is employed to analyse the frame, with geometry, material properties, and loading conditions defined to assess the global structural response [6]. For visualization of the framework, OpenSeesPyView, a Python programming-based graphical user interface (GUI) for OpenSeesPy, is utilized [7]. A benchmark structure found in literature is also modeled for calibration [8, 9].

The parameters defined in the model are listed in Table 1, and the geometric dimensions are shown in Figure 1. The materials used are *Concrete01* for both confined and unconfined concrete, and *Steel02* for the reinforcement, as described in Figure 2.

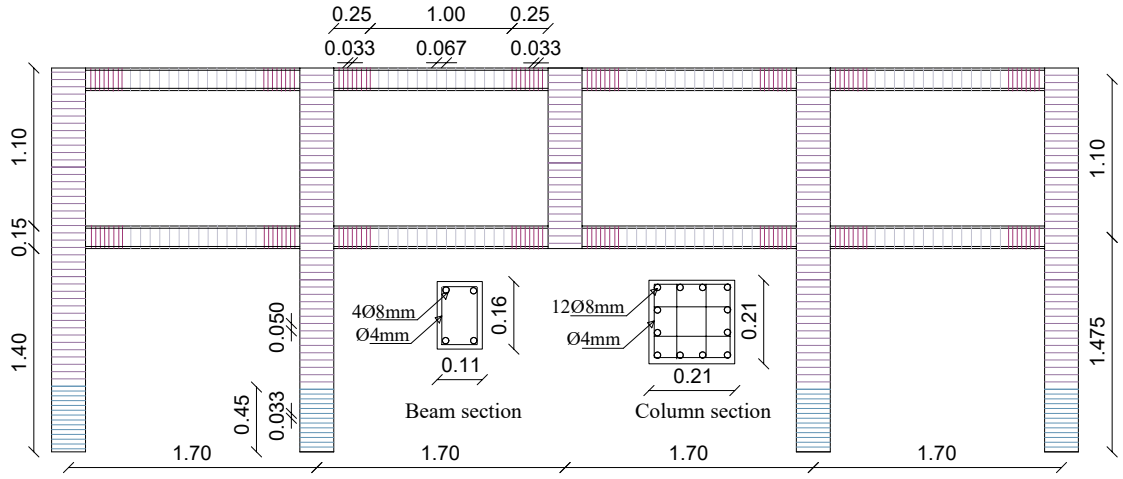


Figure 1. Structural design for the bare frame. Units in meters. Adapted from [8].

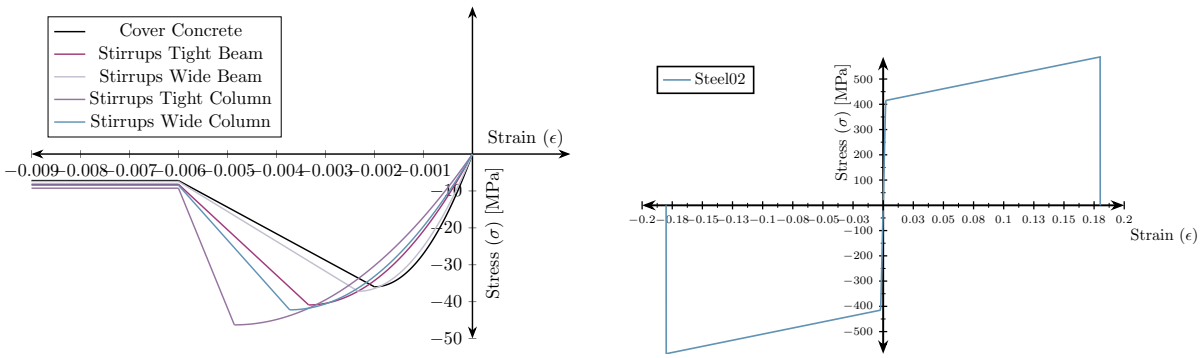


Figure 2. Constitutive models of materials.

The elements are modeled using nonlinear beam-column elements described in layers (*fiber section*), which is a cross-sectional model that considers the distribution of stresses and strains along the section. The advantage of this model lies in its ability to capture inelastic processes without the need to define a plastic hinge length in the model. Additionally, it is possible to define different layers of elements, such as the unconfined concrete cover, the layer of longitudinal reinforcement bars, and the confined concrete in the region inside the reinforcement bars.

For each structural element, the number of subdivisions was defined, and for each subdivision, the number of integration points was specified. For the analysis, the central column was removed, as shown in Figure 1.

Table 1. Material properties and dimensions of the structural elements.

Material Properties	Value [MPa]
f_c (average of compressive strength of concrete)	36
f_y (yield strength of the reinforcement - longitudinal)	415
f_{yw} (yield strength of the reinforcement - transversal)	235
E_s (elasticity modulus of the reinforcement)	201000
Steel reinforcement	[mm]
ϕ_l (longitudinal)	8
ϕ_t (transversal)	4

During the pushdown analysis, the stress–strain response at all integration points was recorded. In the cross-section, the coordinates of the rebar layers at the top and bottom were defined. To analyse the damage in the concrete, the cross-section was divided into layers, and the stress–strain response of each layer was recorded.

The number of files was determined based on the number of elements and concrete layers, as shown in the Equation (1)

$$n_f = n_e \cdot n_{b+c} \cdot (n_{rl} + n_{cl}), \tag{1}$$

where n_f is the number of files, n_e is the number of elements, n_{b+c} is the number of beams and columns, n_{rl} is the number of reinforcement layers, and n_{cl} is the number of concrete layers. The final strain value at each integration point was then analysed. With a mesh with eight elements for beams and columns and sixteen layers for the concrete, the number of files generated was 2448. The code was developed to read the files and identify the points where the material exceeds the limit.

For the longitudinal reinforcement, the limits are defined as the yield strain (ε_y) and the ultimate strain (ε_u), which are 2‰ and 18%, respectively. The damage in the reinforcement is calculated using Equation (2), where ε is the strain at the integration point at the end of the analysis.

$$Damage_{rebar} = \left| \frac{\varepsilon - \varepsilon_y}{\varepsilon_u - \varepsilon_y} \right| \cdot 100 \tag{2}$$

For concrete, the limit was defined as the strain at maximum compressive strength (ε_c), which is -2%. The damage in the concrete is calculated by considering the number of layers in the cross-section that exceed this limit.

3 Results

With the calibration, the pushdown curve was obtained, as shown in Figure 3. This curve is consistent with the experimental and numerical results found in the literature [8, 9]. The simulation also allowed the observation of the damage mechanism, as illustrated in Figure 5, which shows the damage in the top and bottom reinforcement, as well as in the concrete cross-section. Figure 4 presents the deformed shape of the structure, along with the experimental frame.

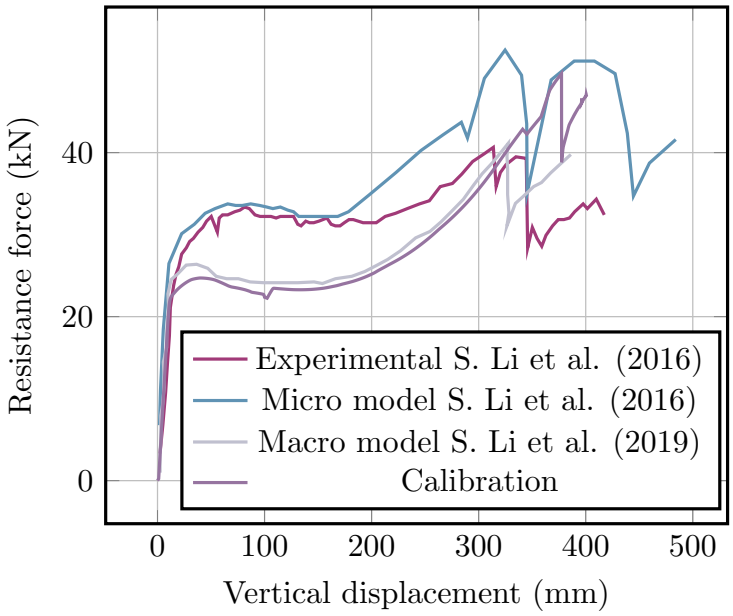


Figure 3. Pushdown curves.

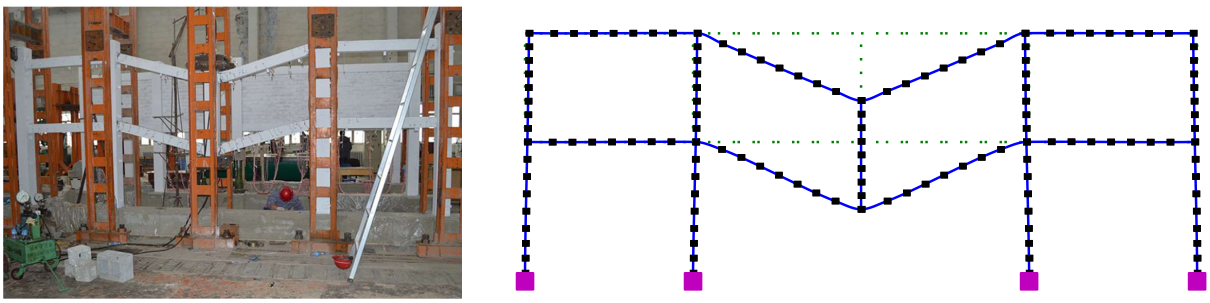
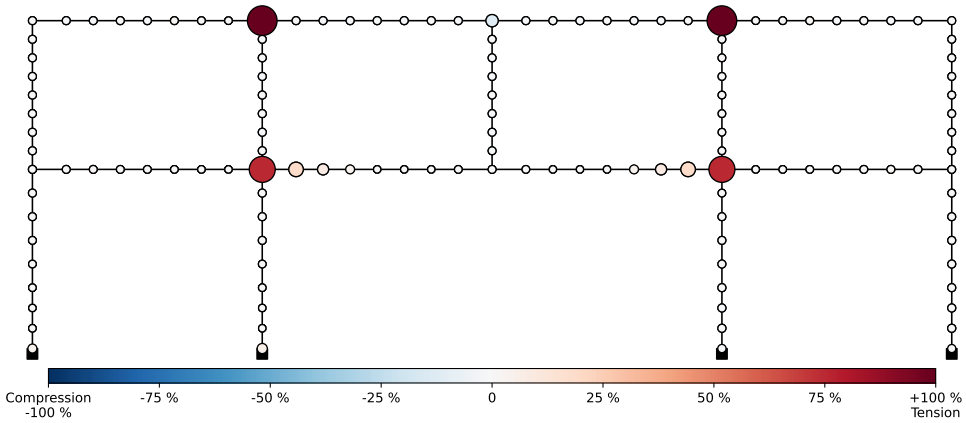
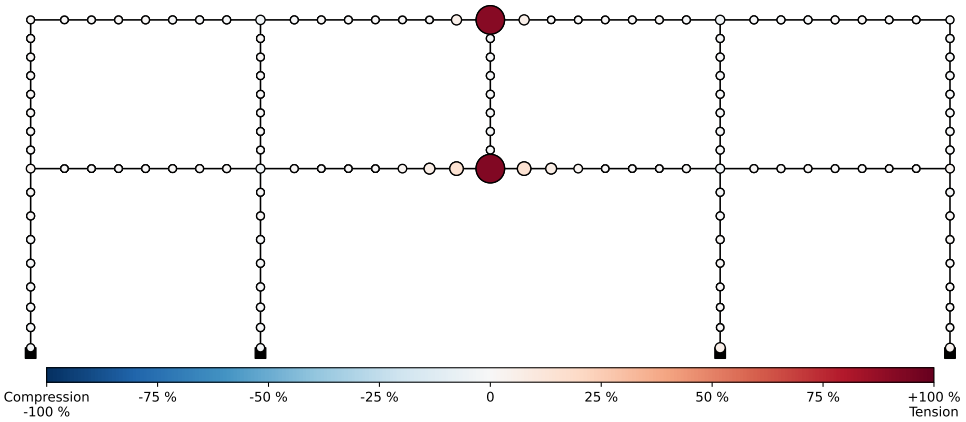


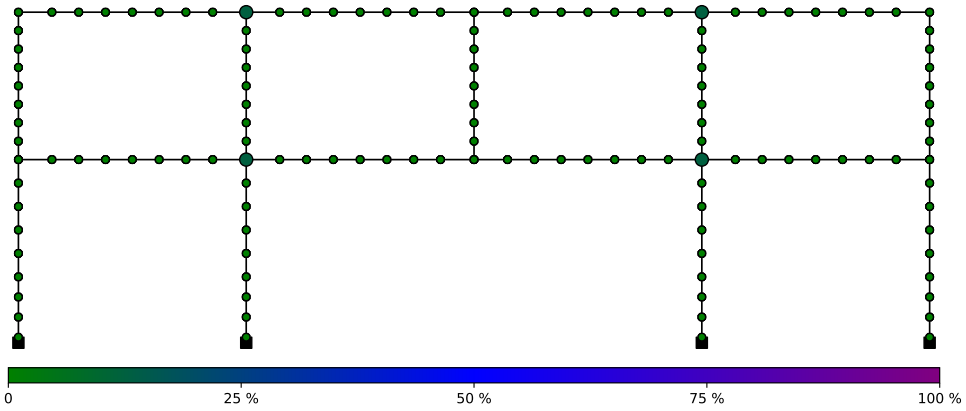
Figure 4. Deformed structure.



(a) Top longitudinal reinforcement.



(b) Bottom longitudinal reinforcement.



(c) Concrete damage.

Figure 5. Damage in the pushdown analysis: (a) top steel, (b) bottom steel, (c) concrete.

4 Conclusions

Based on these results, it can be concluded that the code is functioning properly and the model is capable of approximating the main phenomena of the pushdown analysis. It is important to note that the damage mechanism aligns with expectations, as frame structures typically exhibit a concentration of stress at the connections between beams and columns. It is possible to see that the rupture of the rebar occurs at the top of the structure in the top reinforcement and in the middle of the structure in the bottom reinforcement. For concrete, the damage is concentrated in the beam-column connections near the centre of the structure, in the span where the column was removed.

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