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A Module to Capture ASCE 41 URM Mechanisms in Perform-3D to Analyze and Retrofit 3D Buildings for World Bank Retrofit Program in Kyrgyzstan

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ABSTRACT

Unreinforced masonry (URM) buildings are a common but seismically vulnerable construction type in developing countries. In Kyrgyzstan in Central Asia, the World Bank aims to provide the most impactful retrofit solutions for over three thousand schools with the given funding. URM buildings have complex in-plane failure mechanisms including rocking, toe-crushing, diagonal tension, and bed-joint shear per ASCE 41, in addition to soil plunging, soil friction and complicating effects of boundary elements. These mechanisms must be accounted for in the evaluation to provide effective retrofit designs. This paper describes a powerful module-based modeling technique to analyze URM buildings in Perform-3D. A unit module is developed that captures all the above in-plane failure mechanisms. The unit modules are then integrated into a wall profile to create perforated and solid 2D walls, which are then combined to form a 3D building model. This modeling technique is applied to analyze representative schools and obtain existing building pushover curves. Based on the observed critical failure mechanisms, incremental retrofit solutions are developed by altering the properties of the modules in the analysis. The proposed module-based approach provides an effective tool for analyzing and retrofitting whole URM buildings.

Introduction

URM buildings are a common seismically vulnerable building type in developing countries, yet many prevalent analysis software do not have built-in capabilities for evaluating whole URM buildings. For a World Bank Retrofit School Program in the Kyrgyz Republic, it became necessary to analyze multiple types of URM buildings to assess risk and provide retrofit strategies. As a solution, we developed a method of modeling and capturing the URM in-plane behavioral mechanisms in Perform-3D.

The URM failure mechanisms are varied and complex. During an earthquake, URM buildings can undergo different in-plane failure mechanisms like rocking, toe-crushing, diagonal tension, and bed-joint shear per ASCE 41, as shown in Figure 1a. In addition, other possible failures include soil plunging, soil friction and the failure mechanisms can be further complicated by the presence of boundary elements. In this paper, out-of-plane wall failures are not considered, as slender walls were recommended to be replaced. The in-plane failure mechanisms in URM buildings depend on the material properties, wall thickness, aspect ratios, openings and tributary loads as well as presence of boundary elements and soil properties. Some of the mechanisms such as toe-crushing and diagonal tension are brittle failures, whereas others like rocking and bed-joint sliding are more ductile failures. The method of capturing these various mechanisms in a unit module is described next.

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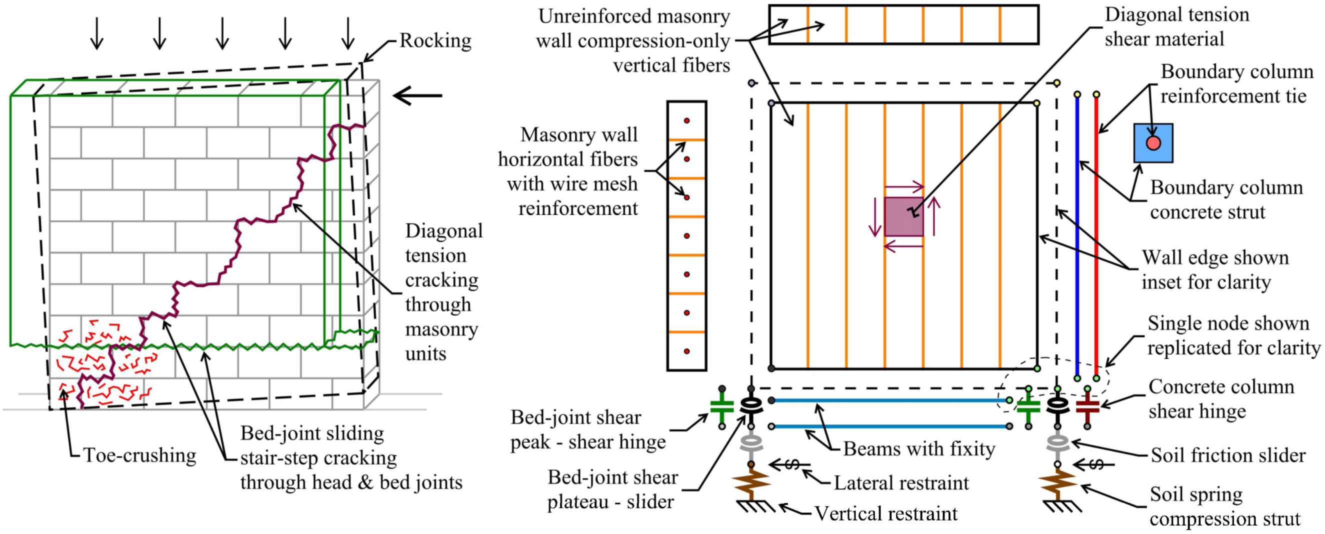


(a) ASCE 41 URM Mechanisms (b) Module definition in Perform-3D

Figure 1. ASCE 41 URM In-plane failure mechanisms captured using a Module in Perform-3D.

A Module to capture URM In-plane failure mechanisms

To enable flexibility in analyzing many different types of buildings, we decided to create a versatile unit module representing a URM wall panel that captured the different URM failure mechanisms. The module was iteratively developed by adding incremental refinements to capture additional failure mechanisms while maintaining the functionality of the earlier defined failure mechanisms. The resulting module is described in this paper and is graphically conveyed in Figure 1b, where the elements of the module that overlap between the same nodes are shown separated (and the common nodes replicated) for clarity. Figure 2 shows the deflected shapes and pushover curves for these different mechanisms simulated using the module. The material back-bone curves are per ASCE 41, using expected strengths found in the Kyrgyz Republic. The text below describes how each of the URM mechanisms were modeled in the module.

(a) Rocking mechanism is modeled using friction pendulum seismic isolators (sliders), as they allow for uplift and can also capture other sliding mechanisms like bed-joint sliding and soil friction.

(b) Toe-crushing mechanism is modeled using inelastic wall fibers with a specified material backbone curve for masonry. As there is typically no vertical reinforcement in URM buildings, the vertical wall fibers are modeled as unreinforced. In Central Asia, the masonry buildings typically have some small wire mesh reinforcement in the horizontal direction, so the horizontal masonry wall fibers are modeled with the wire mesh reinforcement.

(c) Bed-joint sliding pushover response per ASCE 41 comprises of a peak followed by plateau in the pushover curve, see Figure 2c. This mechanism is captured by using a combination of shear hinge and a slider element. The slider element captures the plateau portion of the backbone curve. The shear hinge captures the peak shear strength in excess of the strength of the plateau. These two elements are placed in parallel, and their additive responses result in the desired pushover curve. Beams, as a portion of the masonry wall or as grade beams at the base of the wall, are added to provide flexural restraint at the ends of the slider elements.

(d) Diagonal tension mechanism is modeled by assigning an equivalent inelastic shear material to the wall, with strength capacities calculated using the equations in ASCE 41.

(e) Soil friction mechanism resulting from the building sliding at the base is modeled using sliders.

(f) Soil plunging mechanism is modeled using compression-only struts to capture failures in soil bearing pressure due to inadequate footing footprint or presence of a weak soil.

(g) Additional mechanisms affected by the presence of a reinforced concrete column boundary element are captured by modeling the boundary element, using a combination of concrete compression strut, reinforcement tension tie and a column shear hinge.

The module was vetted by modifying specific parameters to test that each failure mechanism behaved as expected. The resulting pushover curves and element forces were validated by hand calculations.

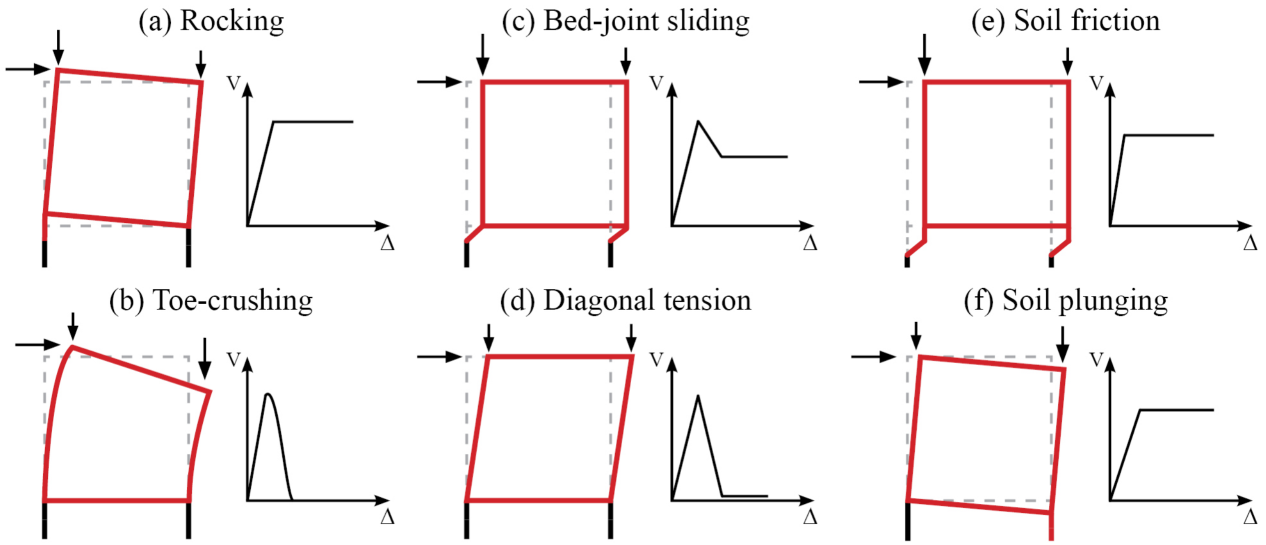

(a) Rocking
(c) Bed-joint sliding
(e) Soil friction
(b) Toe-crushing
(d) Diagonal tension
(f) Soil plunging

Figure 2. Deflected shapes and Pushover curves of URM In-plane failure mechanisms captured by the module.

Building the 3D analysis model using modules

The functionality of the unit module extends to the entire structure when integrated into the building. The unit module can be resized and combined into a typical wall panel, meshed per ASCE 41 aspect ratio, then stacked vertically and horizontally to create solid or perforated 2D frames and 3D building models. Figure 3 shows some examples of the different building types that were modeled and analyzed in Perform-3D. In a solid wall panel, the unit module comprises the entire panel and the critical sliding plane is modeled at the base of the story. In a perforated wall with windows, the unit module comprises the wall pier between openings, and the critical sliding plane is modeled at the base of the window. A sampling of typical unit modules in both perforated and solid walls within a 2D frame are shaded in blue in Figure 4a for clarity. The remainder of the wall panel comprises of typical URM wall material. At perpendicular wall intersections, shared nodes are defined at stable nodes, not in the sliding plane.

Additional modifications are appropriate depending on module location and wall profile. At the upper levels, the soil springs are deleted, and the soil friction coefficient increased to deactivate the soil failure mechanisms. The peak strength capacities for the bed-joint shear hinges are modified depending on the wall length tributary to the shear hinges. For adjacent modules, end fixity of the beams at the sliders are modeled as fixed-pin so that each slider has a fixity on only one side, whereas for stand-alone and end modules, the beams are fixed-fixed.

After modeling the geometry with the unit modules and wall panels, element properties were refined, gravity loads assigned, and precast concrete diaphragms modeled as rigid. The wall self-weight was calibrated to compensate for the area of wall lost at the modeled sliders. To validate the behavior of the assembled 2D walls and 3D buildings, parametric pushover analyses were performed to vet different mechanisms. Figure 3 shows the deflected shapes and non-linear pushover analysis results for two different building types.

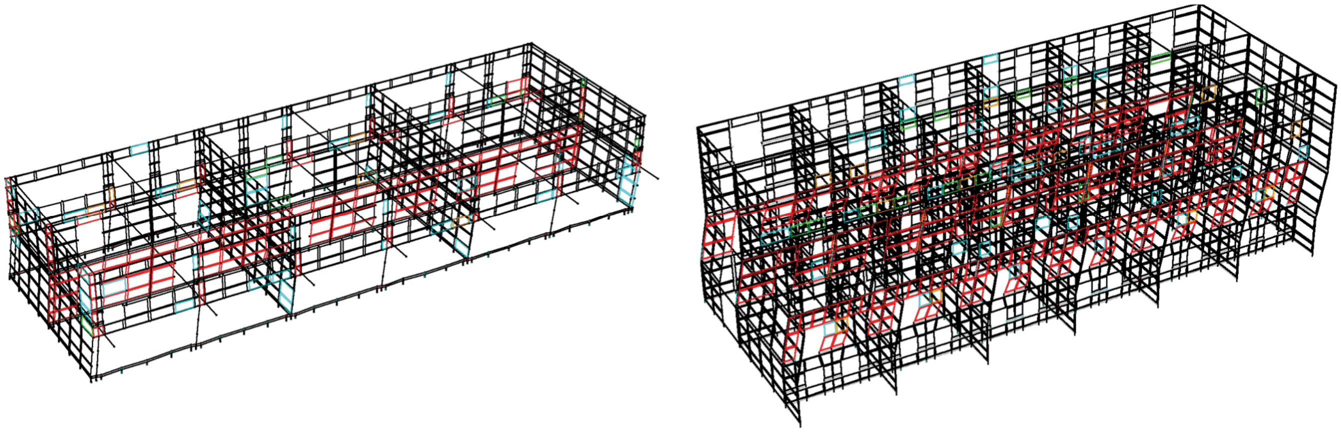
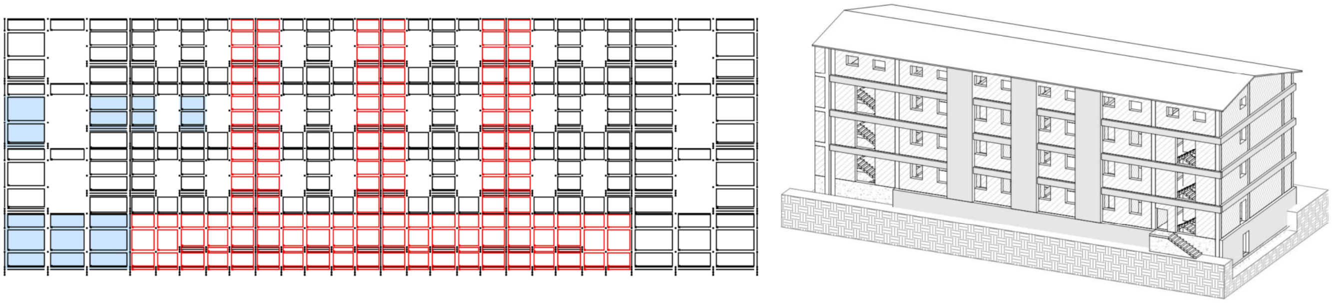


Figure 3. Perform 3D model pushover snapshots for different building types.

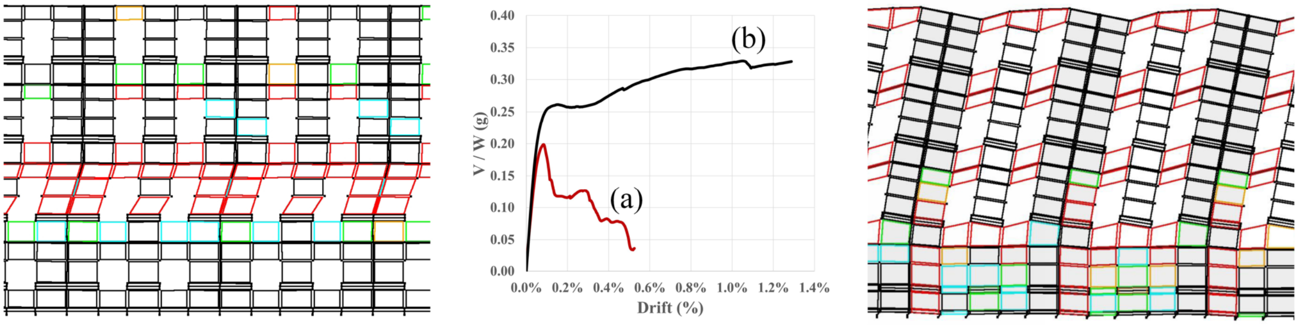
Developing retrofit solutions

The unit module approach to modeling and analyzing whole buildings enabled us to determine the existing building pushover strength and develop tailored retrofit solutions. To model a reinforced concrete wall where added for retrofit, the module properties were modified with reinforced concrete inelastic wall fibers and shear material. The retrofit wall was modeled overlapping the sliders to preclude the occurrence of bed-joint shear failure in the retrofitted state. Figure 4a shows the extent of the reinforced concrete retrofit walls highlighted in red, at an exterior longitudinal wall (also shaded in grey in Figure 5b). Figure 4b shows a snapshot of the same wall in the structural Revit model. Figure 5 compares the brittle story shear failure mechanism before retrofit with the stronger and more ductile flexural mechanism after retrofit. The resulting building pushover curves are also presented. Increasing levels of retrofit were analyzed and developed to provide greater levels of earthquake safety. The existing and retrofitted analyses and drawings were used to obtain corresponding seismic risk and associated retrofit cost estimates. The comprehensive risk assessment helped the World Bank decide which level of retrofit for how many school buildings was the best use of their investment. Interested readers are directed to the ATC-148 [2] and ATC-142 [1] project reports.



(a) Retrofit model highlighting reinforced concrete walls in red (b) Retrofit drawings - 3D Revit model

Figure 4. Analyzing and designing retrofit solutions by modifying the properties of the modules.



(a) Before retrofit 3D building pushover curves (b) After retrofit

Figure 5. Comparison of 3D building pushover curves and failure mechanisms – before and after retrofit.

Conclusions

The paper describes a methodology to model and predict URM in-plane failure mechanisms in Perform-3D. The unit modules both individually and collectively capture the different URM mechanisms, making them an effective tool for modeling and evaluating whole buildings. This module-based modeling approach was used to analyze and develop retrofit solutions for URM buildings in Kyrgyzstan, and we hope that this paper proves useful to others seeking to retrofit URM buildings around the world.

Acknowledgments

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