

## Development of a Benchmark Model for Irregular Structures

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### Summary

*Many building structures have non-symmetric floor plans or multiple towers and setback floors. Such buildings are prone to earthquake damage due to coupled lateral and torsional movements producing non-uniform displacement demands in building elements and concentrations of stresses and forces on structural members. Current codes fall short of providing recommendations for irregular structures. Thus, there is an apparent need to develop a simple analysis procedure based on rigorous analytical and experimental information on the inelastic seismic response of irregular structures. An experiment was designed and carried out to better understand the nonlinear inelastic seismic response of irregular structures. A new structural (benchmark) model was designed in such a way that damage affects sacrificial elements only while most parts are retained for further use. The model was also designed for easy reconfiguration. Test results show that permanent deformations and asymmetric mode shapes are visible and that damage occurs due to irregularities. Results from a recent shaking table experiment are used to develop a simplified analytical tool for irregular structures based on the “spectral capacity analysis” concept.*

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### Introduction

Structural irregularities are commonly found in constructions and structures. Architectural demands are usually the cause of such irregularities. The analysis of the seismic response of irregular structures is complex due to nonlinear and inelastic response and more difficult than that of regular structures. There are very few experiments on globally irregular assemblies. A shaking table study was performed using a new reconfigurable model to obtain data for calibration and benchmark of analytical studies. The experiment is intended to provide a better understanding of the effect of irregularities on the structural seismic response near collapse. Results are also used to calibrate analytical models currently under development. Moreover, the model developed for this study will be used further as a test-bed for hybrid structures and new protective systems and energy dissipation devices.

### Objectives

The objectives of this study are:

1. Develop a model with separated vertical and lateral load resisting systems and capable to sustain damage in sacrificial elements without collapse (the model is developed as a BENCHMARK MODEL for the analysis and testing through the Networking Program)

2. Develop a retrofit strategy for hybrid structures with separated lateral and vertical supporting systems using supplemental energy dissipation devices
3. Develop simplified evaluation procedures for irregular structures
4. Determine performance limits for irregular structures, i.e., calibration of techniques of fragility evaluation (Barron-Corvera 2000).

## Methods

The model is a 3-story steel structure with two unequal towers, i.e., it has a vertical irregularity. The scale of the model is 1:3. The model is designed to behave in a ductile manner and to allow collapse to occur in the lateral load resisting system. The plan dimensions of the model (6m x 2m) were defined in accordance with the size of the shaking table. Views of the benchmark model are presented in Figure 1. The undamageable gravity load resisting system is separated from the damageable lateral load resisting frames. The gravity load resisting system consists of rocking columns and slotted connections are implemented in the lateral load resisting frames. Special features of the model such as the gravity load columns, the slotted connections and the 5-directional load cell used to measure the structural response are shown in Figure 2. The model has a versatile configuration due to its removable elements and can be used for experimental studies of different structural configurations, protective systems or energy dissipation devices. Figure 3 shows possible layout arrangements of the model.

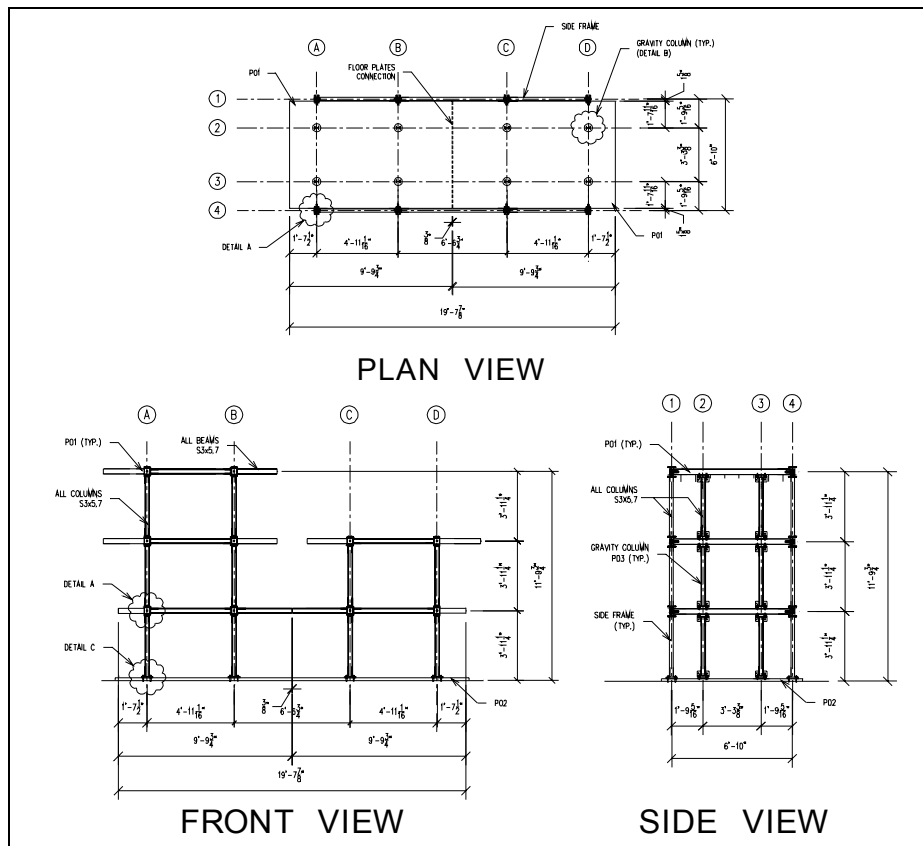
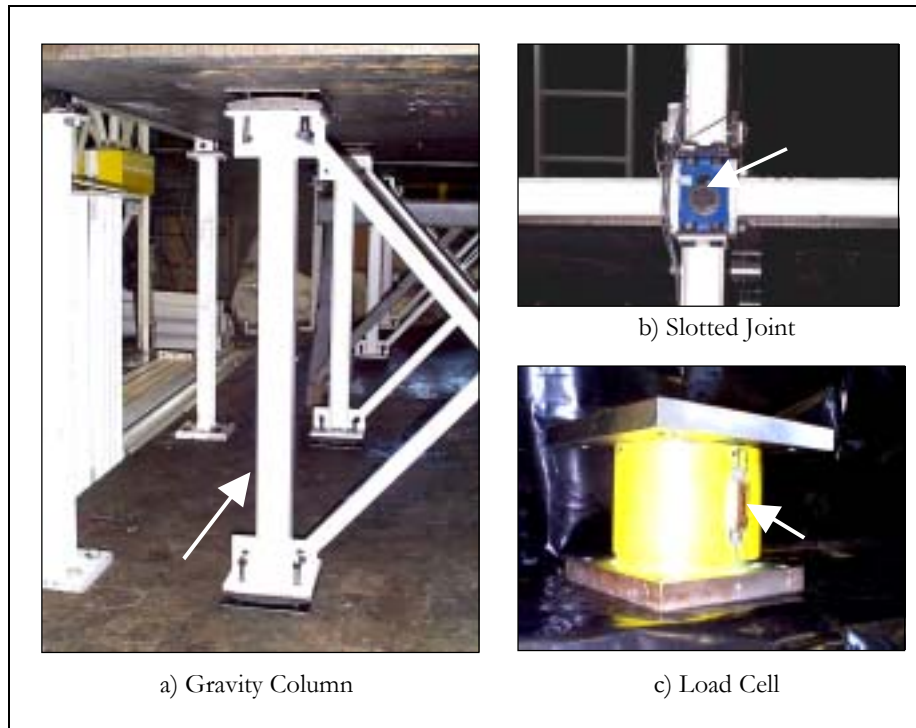
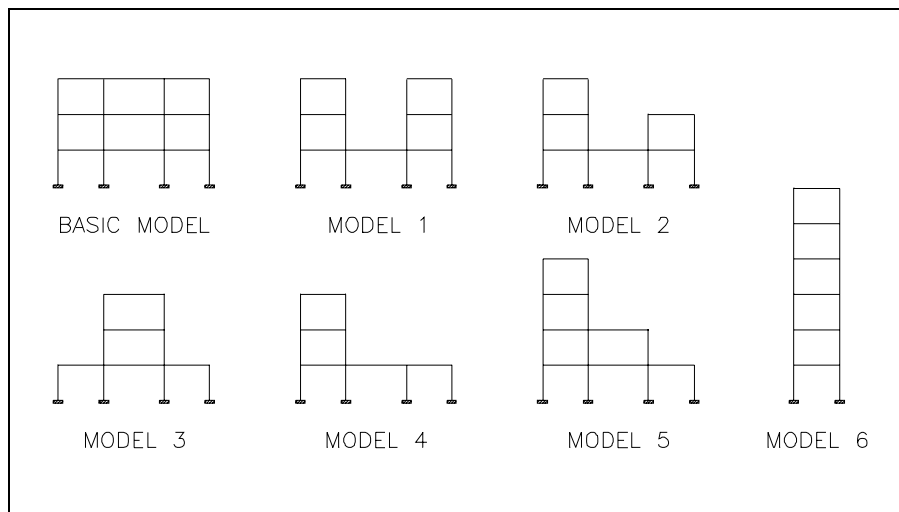


Figure 1. Structural drawings of the model



**Figure 2. Special features of the benchmark model**



**Figure 3. Possible layout arrangements of the model**

### Test and Analysis

The model (type 2) was subjected to the Rinaldi Station (LA16) earthquake record of the 1994 Northridge earthquake scaled to increasing values of PGA. Static and Dynamic (Incremental) Pushover Analyses were performed using IDARC2D and LARSA software platforms. Initial analyses show that the model develops irregular response in terms of curvatures and generalized forces (Figure 4).

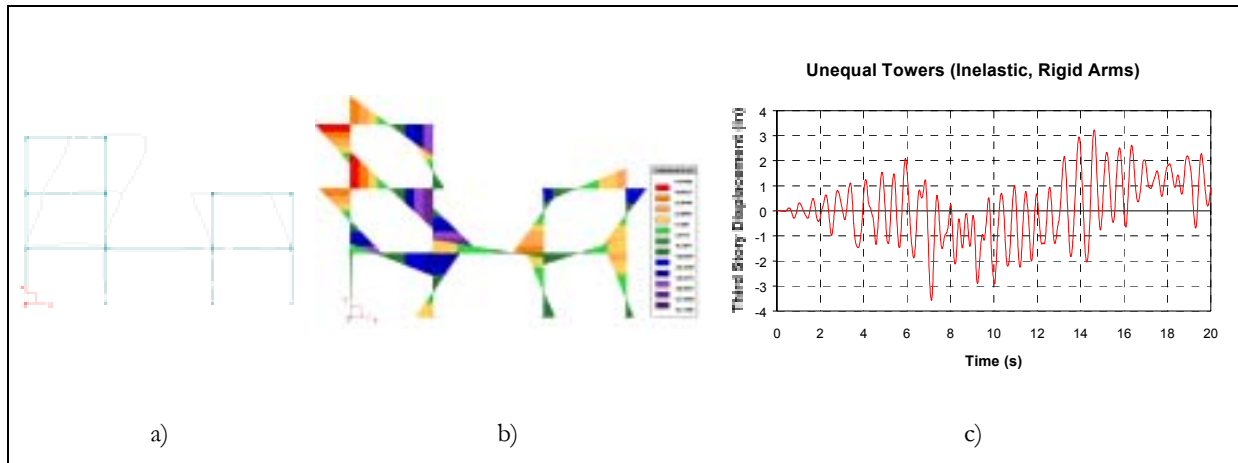


Figure 4. Inelastic displacements and forces

An experimental study was conducted following the Dynamic Pushover Analysis approach. The model (Figure 5) was subjected to the same ground acceleration history mentioned before (LA16) scaled to increasing values of PGA. Test results show that the fundamental period of the model is 0.60 sec and that the model behaves inelastically when the base shear is greater than 20% of the weight of the model. The experiment shows that damage occurs mostly on beam-column connections in the form of prying effects in column end plates and welding failures of rigid connection (Figure 6).

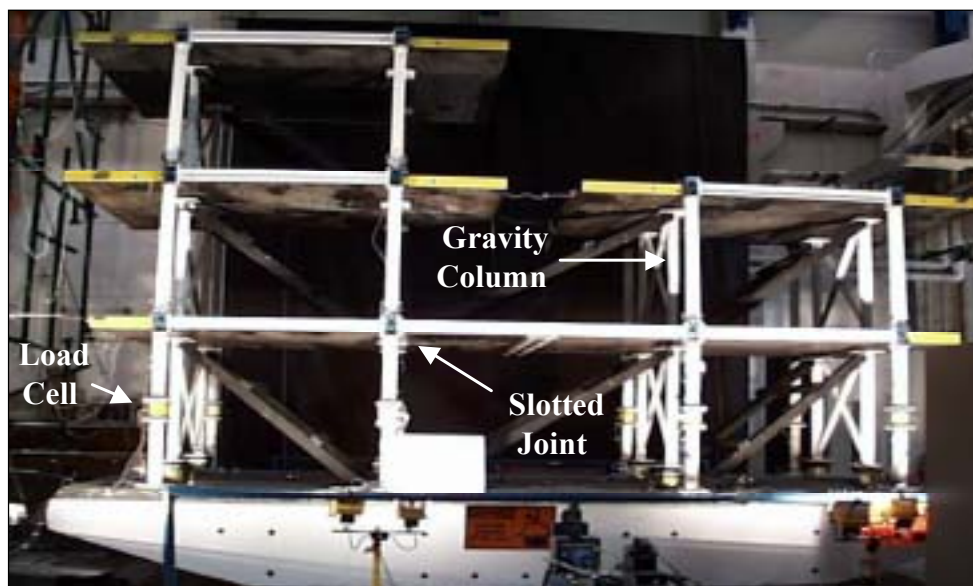


Figure 5. View of the test setup

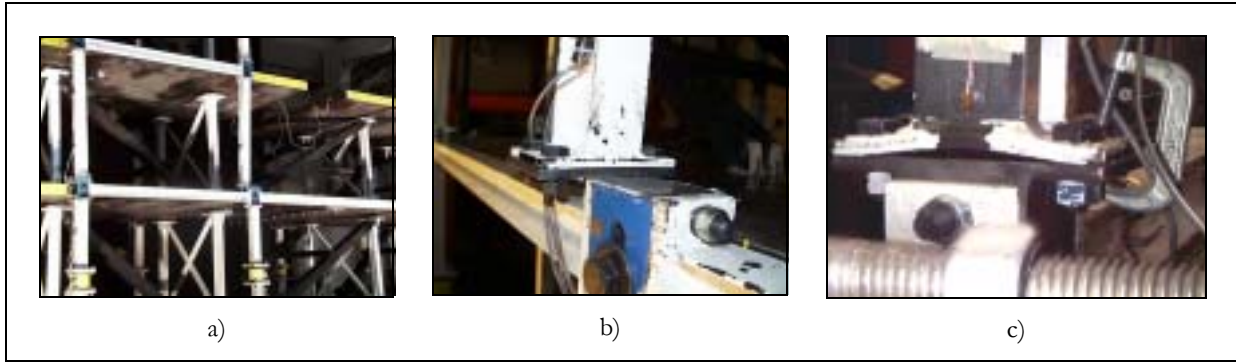


Figure 6. Damage on elements of the model

### Work in Progress

Preliminary testing of joints and components indicated that the benchmark model has actually semi-rigid connections. A new computational model for these connections was developed and the structure was re-evaluated. As a result, more fail-safe guards were added to the benchmark model and the computer program (IDARC2D) was enhanced by incorporating an additional connectivity model (Figure 7).

Comparison between experimental and analytical results (Figure 8) shows that the new computational model predicts well the behavior of the model under seismic excitations. In contrast, the original computational model with adjusted parameters (“strong” or “weak” in Figure 8) would not be able to predict the response to ground shaking.

Upon completion of the analyses, the model will be retrofitted with dampers attached to the rocking columns. This work will be done in cooperation with Taylor Devices, Inc. (Tonawanda, NY).

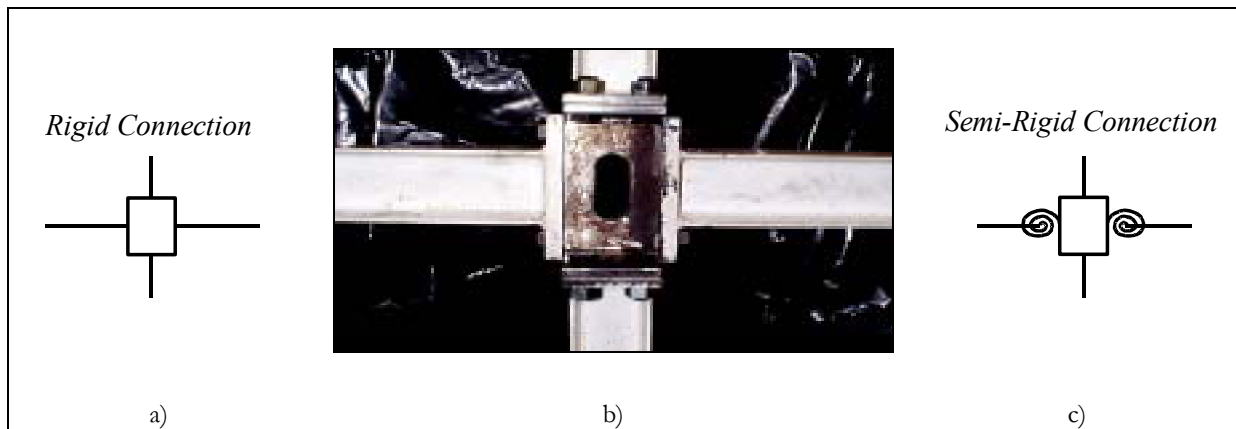


Figure 7. Computational model for connectivity

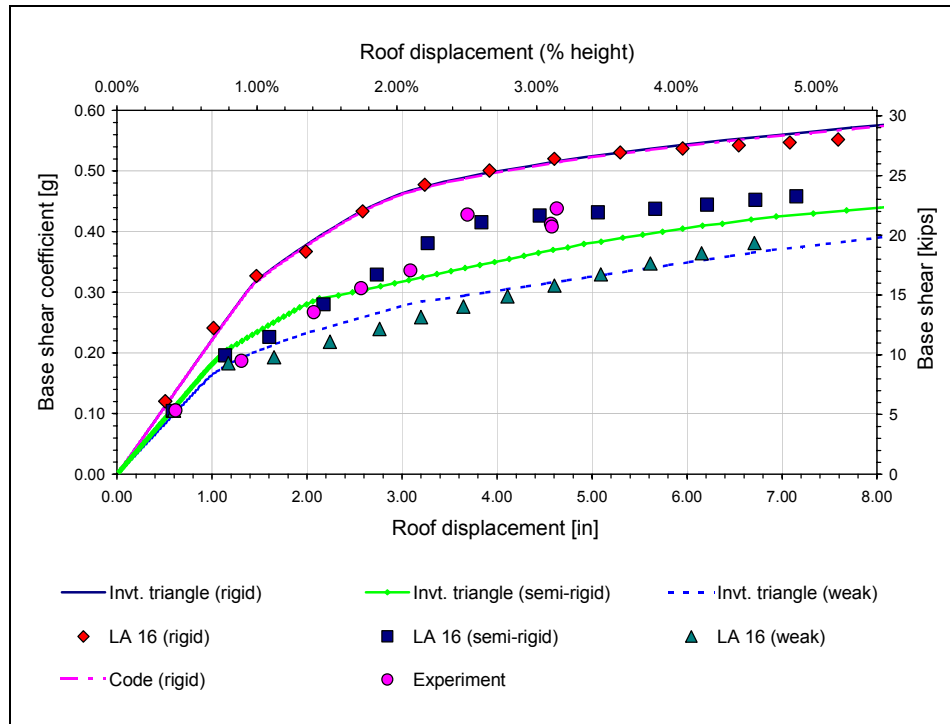


Figure 8. Comparison of analytical and experimental results

## Conclusion

Experience shows that buildings with irregularities are prone to earthquake damage, as observed in many earthquake occurrences. Since current codes fall short of providing simplified analytical tools for irregular structures, it is necessary to develop a simple analytical procedure based on rigorous inelastic computations and experiments on the seismic response of irregular structures. Since there are very few analytical models validated by experiments, an experiment was carried out to better understand the nonlinear inelastic behavior of irregular structures under seismic excitations. Test results show that damage occurs due to irregularities. Further studies will be carried out to develop a simplified analytical tool for irregular structures based on the “spectral capacity analysis” concept.

## Acknowledgements

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## References

Barron-Corvera R (2000): Spectral evaluation of seismic fragility of structures. *Ph.D. Dissertation*, Department of Civil, Structural & Environmental Engineering, University at Buffalo, Buffalo, NY.