Collapse Simulation of Multi-Story RC Buildings through Hybrid Testing

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Abstract

Collapse probability assessment of structures requires the prediction of a structure's response from the initial linear-elastic behaviour to collapse and thus poses significant challenges. Although there has been much advancement in the mathematical models employed in finite element methods, many of these analytical models are calibrated using experimental observations. Therefore, experimental research remains critical towards better understanding and predicting the seismic response of structural components. From quasi-static cyclic tests, the ductile behaviour and energy dissipating properties of the tested specimen can be obtained, but the effect of the specimen's nonlinear behaviour on the overall response cannot be studied since there is no interaction between the specimen response and the predetermined loading sequence. Hybrid simulation is a cost-effective large-scale experimental method that overcomes this issue by linking the computer simulations to a physical test rig. While applications of this method to date have been mainly limited to planar loading, the objective of this study is to develop a hybrid simulation frame model and control the 6 degrees-of-freedom loading scheme applied to a specific structural component. In this paper the results of coupled-numerical simulations conducted prior to running the experimental hybrid tests are presented for a limited-ductile ordinary moment resistant reinforced concrete frame building (RC-OMRF).

Keywords: experimental methods, hybrid simulation, RC frame buildings, multi-directional loading.

1. INTRODUCTION

One of the main goals of earthquake engineering is to improve the resilience and performance of structures and the understanding of earthquake and their effects on the structural systems and their components. The research concerning the seismic structural response is founded on the basis of theory, model-based computer simulations and laboratory experimental testing. Currently, there are three types of experimental testing to evaluate structural behaviour subject to dynamic loadings, which are shake table testing, quasi-static testing, and hybrid simulation (Filiatrault et al., 2013). Hybrid simulation offers key advantages over conventional testing methods including quasi-static and shake table testing.

Quasi-static testing employs actuators to apply pre-defined load or displacement histories to a specimen, designed to represent the expected loading experienced by the prototype during an earthquake. Large or even full-scale specimens can be used to overcome the effects of scale and size, but the pre-determined test histories often fall short in reproducing multi-directional action expected in the prototype.

Although shake table testing applies a ground motion input to a structure and better captures the dynamic properties of the specimen, the size and capacity of shaking tables often restrict the size and scale of the models. This leads to similitude compensations such as added mass to compensate for the reduced volume of the specimen, and is likely to introduce errors when replicating construction details in small scale.

Evolved from pseudo-dynamic testing (Nakashima et al., 1992), hybrid simulation is a versatile and economically viable experimental technique to evaluate the dynamic performance of large civil structures (Nakashima, 2001). According to a report developed by the US earthquake engineering community in 2010, hybrid simulation capabilities are a major emphasis of the next generation of earthquake engineering research (Dyke, 2010). This method takes advantage of the benefits of the two previous testing techniques by combining a physical quasi-static test with a computer model to simulate dynamic loading. Therefore, instead of using a pre-determined loading pattern, hybrid simulation allows a ground motion input to the model.

Hybrid simulation with substructuring provides significant opportunities to better understand structural behaviour and the capacity of structural members near collapse. While simulating the response of a structure at the system level, the experimental substructures under realistic loads generate new data to contribute towards improved understanding of structural behaviour. Specifically, structural behaviour through collapse has become increasingly important for applications in performance-based design and a few hybrid tests have been conducted to examine structures up to collapse with significant geometric and material nonlinearities (Schellenberg et al., 2008, Shoraka et al., 2008, Wang et al., 2012, Hashemi and Mosqueda, 2014).

Although hybrid simulation has been used for evaluation of the seismic performance of a variety of structures, applications to date have been limited to plane loading and to relatively simple structural systems. In contrast, actions during strong earthquakes are three-dimensional and continuously varying. Thus, assessment of such multi-dimensionally varying actions is essential for understanding of the seismic behaviour of structural components, especially for those in large and complex structural systems. The Multi-Axis Substructure Testing (MAST) system at Swinburne provides the opportunity to control 6-DOF states of force or deformation and thus will be used to conduct these 3D large-scale hybrid simulations.

Prior to conducting the hybrid simulations with the physical subassembly in the laboratory, a series of coupled numerical simulations is conducted to compare the hybrid model with the integrated model and also evaluate the integration scheme parameters for the actual experiments. This paper presents the results of such analysis for a limited-ductile ordinary moment resistant reinforced concrete frame building (RC-OMRF). The collapse simulation is implemented and validated utilizing OpenSees (McKenna, 2011) and OpenFresco (Schellenberg et al., 2009) for numerically-coupled simulations.

2. TEST STRUCTURE

Limited-ductile reinforced concrete frame buildings, representing a high percentage among building stock in regions of lower seismicity, may experience potential seismic safety issues due to reasons related to construction, detailing and non-conformity to current design codes. The reference test specimen in this study consists of a symmetrical three-dimensional five-story (h_1=5m, h_{typ}=4m) five-bay (b=8.4m) RC-OMRF building, which was designed for Melbourne. Fig.1 illustrates the details of the beam and column sections that are identical for all stories.

The frame's elements are modelled using *BeamWithHinges* element type to consider both bending and axial loading. The nonlinear behaviour is demonstrated by using a distributed-plasticity concept where the plastic behaviour takes place in a finite length near the ends of the beam-column element. The lumped plasticity model followed peak-ordinated hysteresis response based on the Modified Ibarra-Medina-Krawinkler (IMK) deterioration model (Ibarra and Krawinkler, 2005) for the flexural behaviour (Fig.2a).

The moment-curvature properties of the nonlinear sections in the beam and column elements are calibrated to the modelling parameters predicted from a series of empirical equations. These empirical equations relate column design characteristics to IMK modelling parameters (Haselton et al., 2008) (Fig.2b).

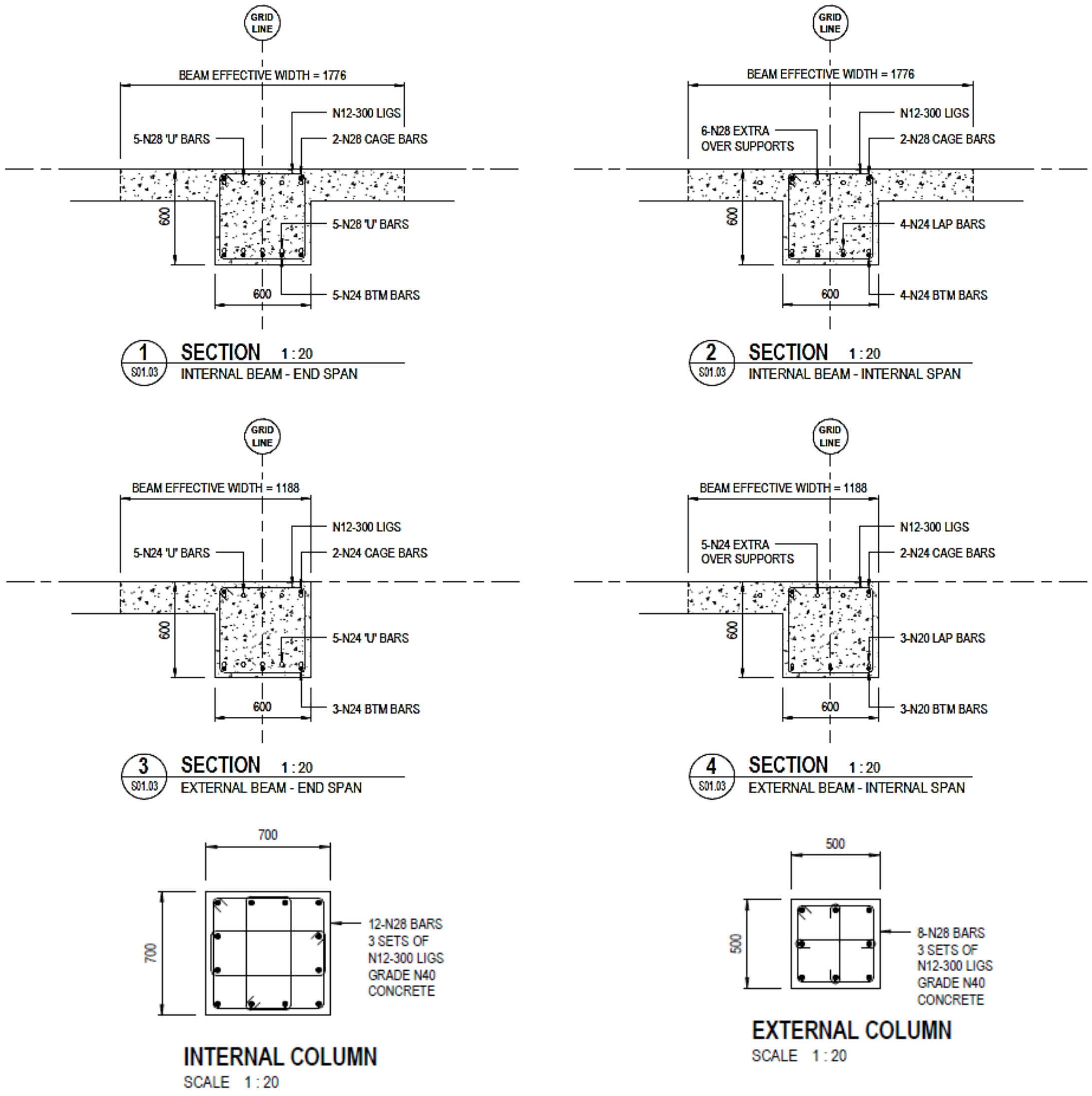
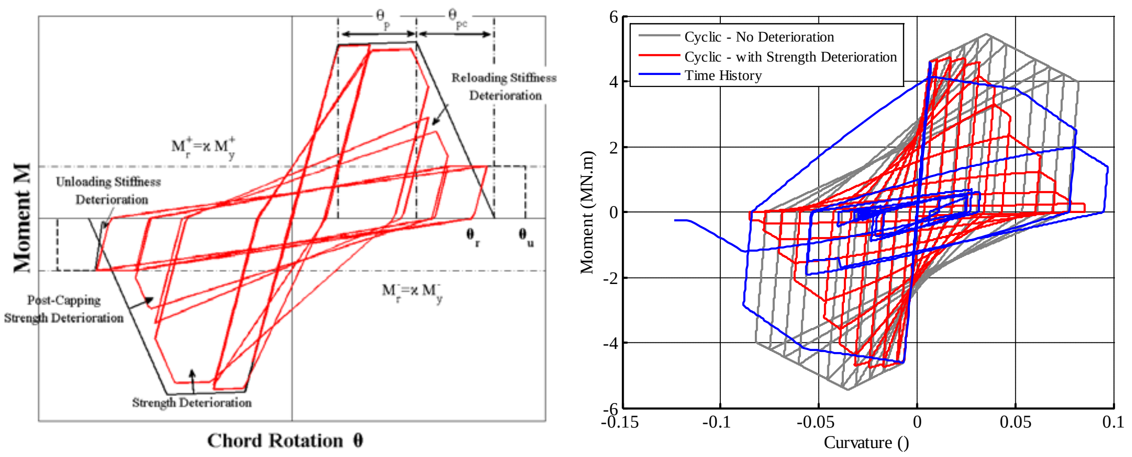


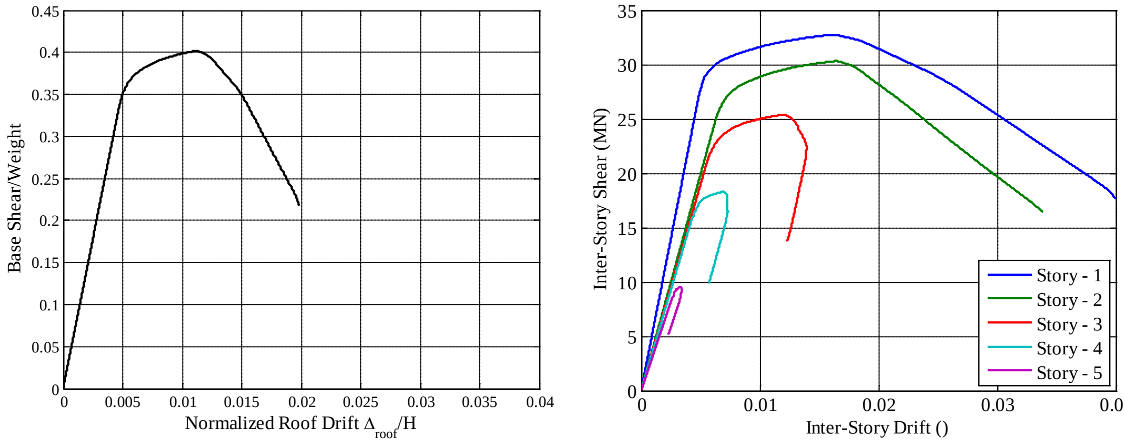
Figure 1. Design details of the RC-OMRF



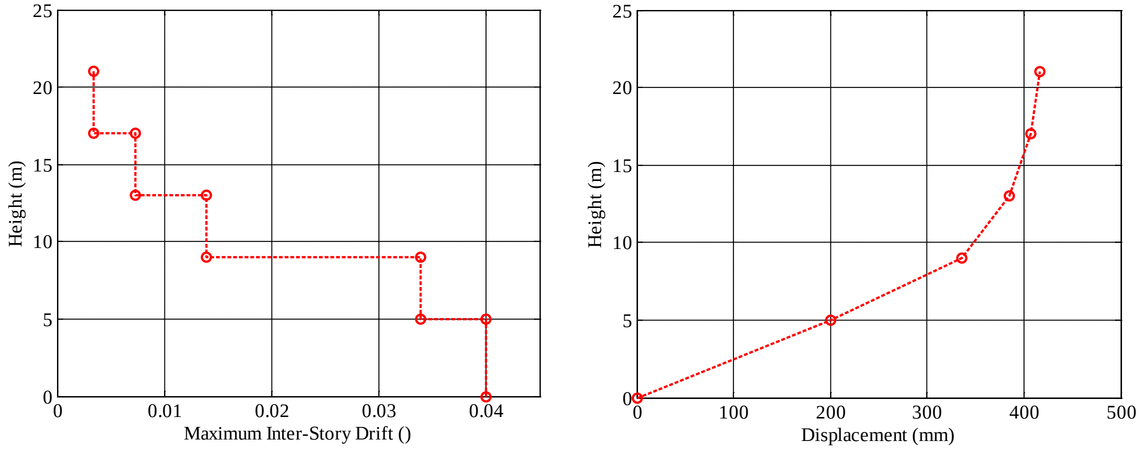
a) OpenSees IMK model b) First-story internal column hinges

Figure 2. Simulation of nonlinear hinges using IMK peak-oriented model

After developing the numerical model, the elastic fundamental period of vibration (T_1=0.887sec) and the corresponding first mode shape were obtained through eigenvalue analysis. A nonlinear static pushover analysis was then performed with the lateral force distribution that is proportional to the first mode until exceeding the point of 20% strength loss. Fig.3 presents the results of the pushover analysis that show most of the energy dissipation occurs in the lower stories.



a) Overall response b) Inter-story response



c) Maximum inter-story drift ratio d) Maximum displacement

Figure 3. Nonlinear pushover analysis

3. HYBRID SIMULATION

Prior to conducting the hybrid simulations with the physical subassembly in the laboratory, a series of coupled numerical simulations were conducted to evaluate the integration scheme parameters for the actual experiments. These numerical studies serve as verification of the substructuring techniques by demonstrating that a partitioned frame model using this approach provides results similar to a full frame model. In the coupling simulation method of two substructures presented by Schellenberg (2008), the numerical substructure takes the role of the master simulation and consists of the numerical subassembly. For these numerical studies, a separate numerical model is provided to represent the experimental substructure and acts as the slave. Both master and slave subassemblies are modelled in OpenSees in these simulations. The equation of motion is solved for the complete system with the slave acting as an 'element' of the master simulation.

During the analysis, the master imposes the displacements on the boundary of the slave subassembly and the slave program returns corresponding forces back to the master program. A generic super-element is connected to the master model and utilized to provide the interactions with the slave model. In addition, adapter elements are added to the slave model to provide the interface with the master model, essentially acting as the actuators to control DOFs in the slave model. OpenFresco is used to connect the master and slave programs through their generic and adapter element interfaces. Later in the actual hybrid simulations, the slave is simply replaced with the experimental substructure. In this study the slave model is the lower-half of the first-story corner column (Fig.4).

The structure is subjected to the bi-directional ground motion of Loma Prieta 1989 with sequentially increasing intensities. To illustrate the method, two levels of ground motion were selected to cover the structure's response from linear-elastic range through collapse. The scale factors for the level of intensities are 0.8 and 1.0 that were obtained from incremental dynamic analysis (Fig.5).

For the full numerical model, the implicit Newmark integration (INM) scheme (Newmark, 1959) with average acceleration method was used with the integration time step equivalent to half of the ground motion time step that is sampled in 0.01sec. The energy increment convergence test was used considering a convergence tolerance equal to 1E-8 and maximum 400 iterations.

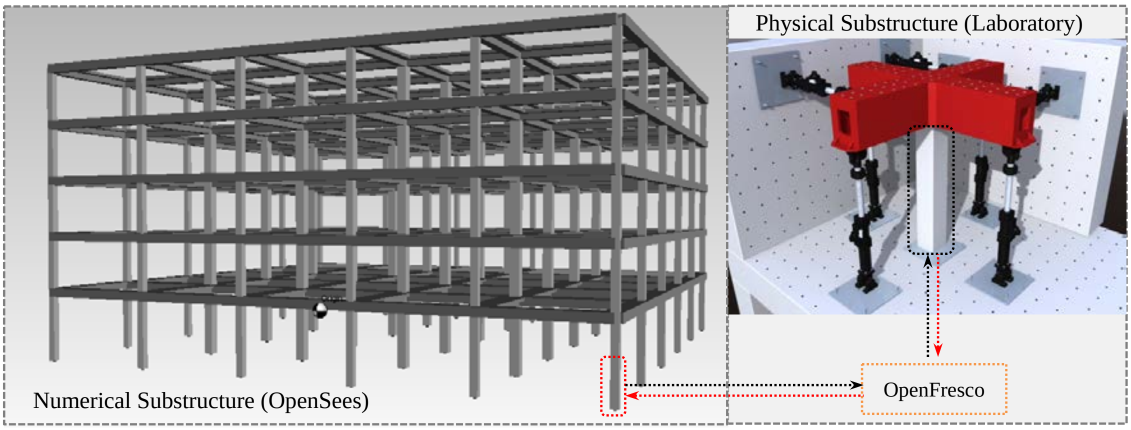
For the hybrid model, however, special requirements need to be provided by the integration scheme that does not allow using the conventional integration schemes (Schellenberg et al., 2009). Some of these requirements are:

1- The process of obtaining the resisting force from experimental elements can be time consuming and introduce errors into numerical integration algorithm and thus the integration scheme should make as few function calls as possible.
2- The integration should provide some adjustable amount of algorithmic damping to suppress the excitation of higher modes due to the experimental errors.
3- Contrary to analytical elements, the experimental element is often unable to return a tangent stiffness matrix and needs to return its initial stiffness matrix instead. This is due to the fact that it is generally difficult to compute an accurate element tangent stiffness matrix solely from the experimentally measured response quantities at the basic or local element degrees of freedom.
4- Since a physical specimen is truly history dependent, the experimental element representing such specimen cannot revert to a previous or initial state of an analysis, once a simulation is in progress. Therefore, displacement increments calculated by iterative procedures are required to be strictly increasing or strictly decreasing within an integration time step.

5- Iterative integration methods should produce displacement increments that are as uniform as possible. This requirement guarantees that the transfer system, which imposes each displacement increment over a typically constant time interval, generates a continuous movement of the test specimen with a uniform speed.

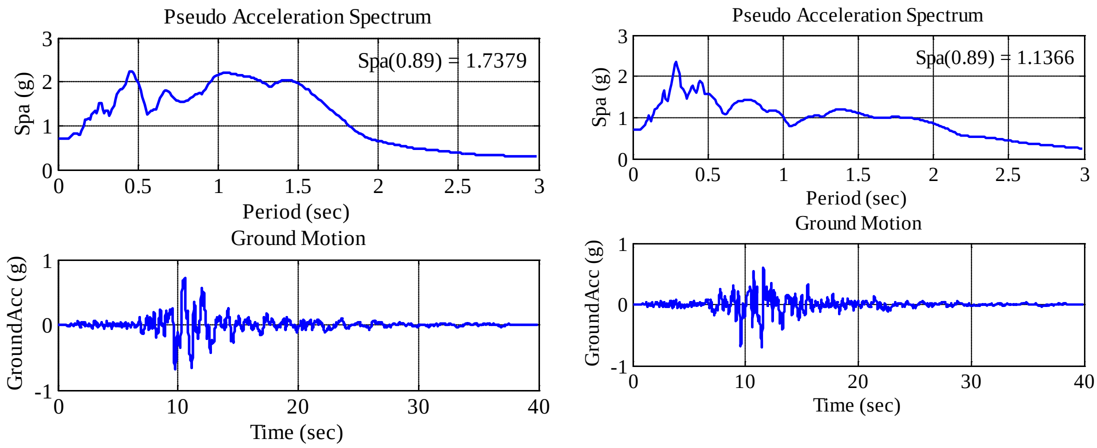
Schellenberg et al. (2009) presented a version of the INM, modified for hybrid simulation. This modified version overcomes the abovementioned problems of implicit integration methods by performing a constant number of iterations per integration step. It should be mentioned that the convergence tests, typically used in iterative integration methods, are removed in the modified version, however convergence parameters are still required to be monitored to guarantee the accuracy and stability of the simulation (Hashemi, 2013).

The modified INM was used for the coupled-numerical simulation of hybrid model with the integration time step equal to the half of ground motion time step and eight fixed number of iterations. The convergence parameters were calculated during the simulation. Fig. 6 presents the comparison of the results for the full and hybrid model utilizing different integration schemes in the in-plane direction where the structure collapses. It can be seen that the results are identical while keeping maximum norm of the unbalanced force vector below 0.08unit, which is very small compared to the maximum base shear (=31.7MN).



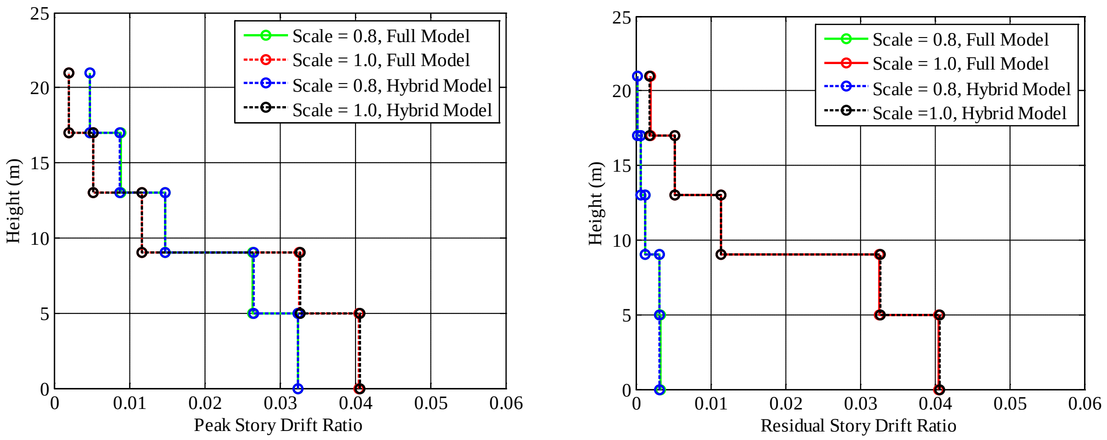
a) Master model b) Slave model

Figure 4. Substructuring the model

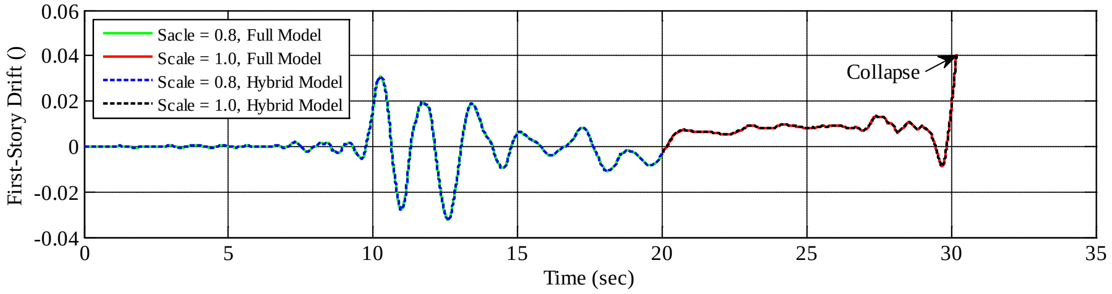


a) In-plane ground motion b) Out-of-plane ground motion

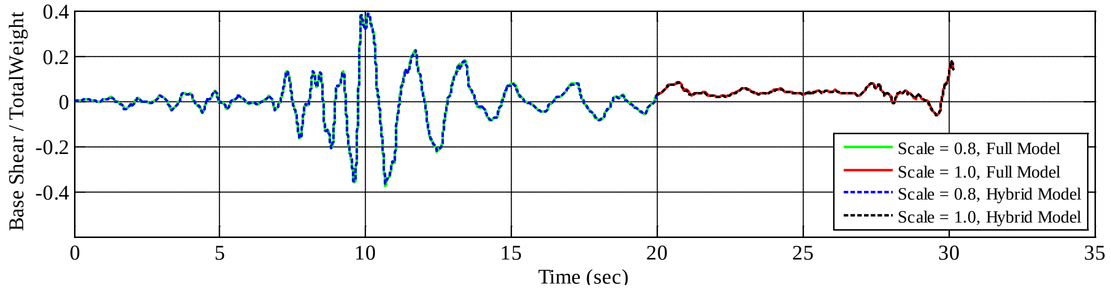
Figure 5. Bi-directional components of Loma Prieta ground motion



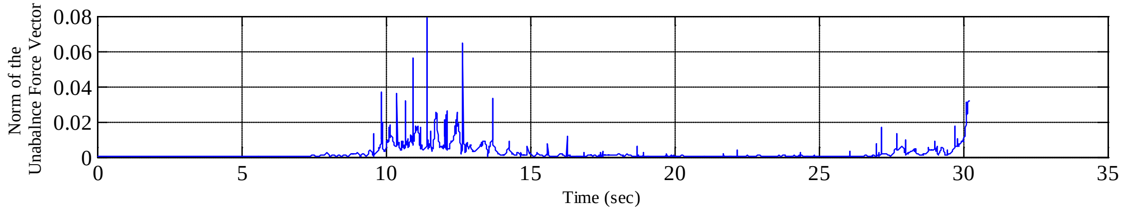
a) Peak inter-story drift ratio b) Residual inter-story drift ratio



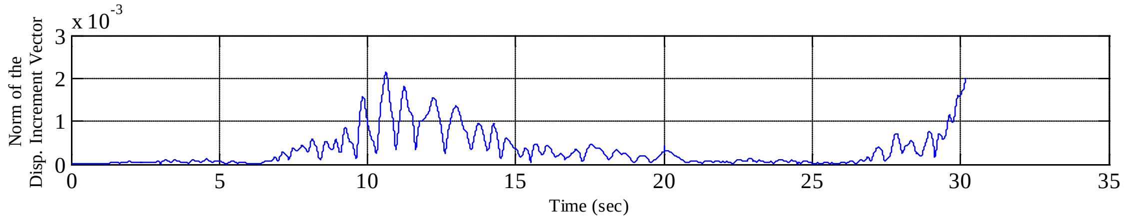
c) Time history of the first inter-story drift ratio



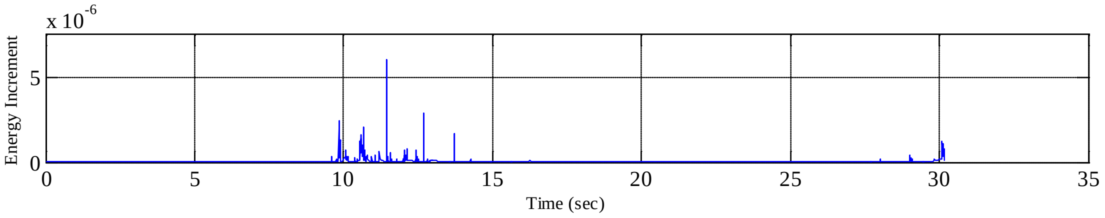
d) Time-history of the base shear divided by the building weight



e) Norm of the unbalanced force vector



f) Norm of the displacement increments



g) Energy increment

Figure 6. Comparison of the full and hybrid model for two sequential ground motions

4. CONCLUSION

A framework for collapse simulation of multi-story structures through hybrid simulation is developed. In this framework the 6-DOF interaction between analytical and experimental subassemblies are controlled during the simulation. Preliminary numerical studies conducted for the accuracy and stability of integration scheme in hybrid simulation of a RC-OMRF structure were also presented that showed identical results comparing the full and hybrid coupled-numerical model, while keeping the unbalance forces below stability margin.

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REFERENCES

Dyke, S. J., Stojadinovic, B., Arduino, P., Garlock, M., Luco, N., Ramirez, J. A., Yim, S. (2010) 2020 Vision for Earthquake Engineering Research: Report on an OpenSpace Technology Workshop on the Future of Earthquake Engineering.

Filiatrault, A., Tremblay, R., Christopoulos, C., Folz, B. & Pettinga, D. (2013) Elements of Earthquake Engineering and Structural Dynamics 3rd Edition.

Haselton, C. B., Liel, A. B., Lange, S. T. & Deierlein, G. G. (2008) Beam-column element model calibrated for predicting flexural response leading to global collapse of RC frame buildings. Pacific Earthquake Engineering Research Center.

Hashemi, M. J. (2013) Collapse simulation of multi-story buildings through hybrid testing with substructuring techniques. In Civil, Structural and Environmental Engineering.) State University of New York at Buffalo, New York, United States, vol. Ph.D., pp. 308.

Hashemi, M. J. & Mosqueda, G. (2014) Innovative substructuring technique for hybrid simulation of multistory buildings through collapse. Earthquake Engng Struct. Dyn.

Ibarra, L. F. & Krawinkler, H. (2005) Global collapse of frame structures under seismic excitations. The John A. Blume Earthquake Engineering Center, Report TB 152.

Mckenna, F. (2011) OpenSees: A Framework for Earthquake Engineering Simulation. Computing in Science & Engineering 13(4):58-66.

Nakashima, M. (2001) Development, potential, and limitations of real-time online (pseudo-dynamic) testing. Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences 359(1786):1851-1867.

Nakashima, M., Kato, H. & Takaoka, E. (1992) Development of Real-Time Pseudo Dynamic Testing. Earthquake Engineering & Structural Dynamics 21(1):79-92.

Newmark, N. M. (1959) A method of computation for structural dynamics. Journal of Engineering Mechanics ASCE 67.

Schellenberg, A., Huang, Y., and Mahin, S. A. (2008) Structural FE-Software Coupling through the Experimental Software Framework, OpenFresco. In Proceedings of the 14th World Conference on Earthquake Engineering.), Beijing, China.

Schellenberg, A. H., Mahin, S. A. & Fenves, G. L. (2009) Advanced Implementation of Hybrid Simulation. Pacific Earthquake Engineering Research Center, Report 2009/104.

Schellenberg, A. H., Mahin, S. A., Yang, T., Mahin, S. & Stojadinovic, B. (2008) Hybrid simulation of structural collapse. In 14th World Conference on Earthquake Engineering.), Beijing, China.

Shoraka, M. B., Charlet, A. Y., Elwood, K. J. & Haukaas, T. (2008) Hybrid Simulation of the Gravity Load Collapse of Reinforced Concrete Frames. In 18th Analysis and Computation Specialty Conference.), Vancouver, BC, Canada.

Wang, T., Mosqueda, G., Jacobsen, A. & Cortes-Delgado, M. (2012) Performance evaluation of a distributed hybrid test framework to reproduce the collapse behavior of a structure. Earthquake Engineering & Structural Dynamics 41(2):295-313.