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HYBRID SIMULATION OF THE GRAVITY LOAD COLLAPSE OF REINFORCED CONCRETE FRAMES

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ABSTRACT

A hybrid simulation test setup is developed to investigate and validate the application of hybrid simulation to the gravity load collapse of reinforced concrete frames. The OpenFresco software framework for hybrid simulation is used in combination with an event-driven real-time predictor/corrector ensuring continuous hybrid testing. A shear-critical reinforced concrete column loaded through three dynamic actuators constitutes the physical substructure while a nonlinear ductile reinforced concrete frame makes up the numerical substructure within the OpenSees environment. This paper presents a nonlinear transformation method designed to allow for an accurate application of the loading on the specimen, and an iterative algorithm with mode-switch to enable the use of force control for the actuators in combination with the displacement-based software, OpenSees. Validation of this hybrid simulation setup will be achieved through a comparison with a shaking table test of the same reinforced concrete frame.

Introduction

The gravity load collapse of a structure during an earthquake involves a complicated interaction between the lateral and vertical capacities of the building. The lack of adequate models capturing this interaction has been identified as a critical deficiency of current methods used to assess the collapse potential of reinforced concrete buildings (Comartin, 2001). Quasi-static and dynamic testing of reinforced concrete columns have been conducted to investigate the shear and axial-load capacity of those members (Minowa et al. 1995, Inoue et al. 2000, Sezen et al. 2002, Ghannoum et al. 2005). However, quasi-static tests imply a predefined loading history and do not account for dynamic effects, whereas shaking table tests are limited in the size and mass of the specimens. Hybrid simulation constitutes the third well-established experimental method for structural seismic testing. The terminology hybrid simulation comes from the fact that a structural system is tested experimentally while its inertia and energy dissipation are simulated numerically. Hybrid simulation also allows "substructuring", i.e. experimental substructures can be included in any finite-element model to perform analyses of large and complex structures. The advantages of using hybrid simulation to assess the collapse potential of structural systems are numerous: physical masses are removed from the experimental setup as they are modeled numerically,

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improving the safety of the tests; the specimens can be tested at large scale; only the vulnerable substructure is tested experimentally while the remaining structure is modeled numerically, improving the economy of the tests; etc. Those benefits make hybrid testing a safe, efficient and less expensive alternative for experimental simulation of structural collapse.

However, several challenges must be overcome to apply hybrid simulation to the structural collapse of reinforced concrete columns: a complex three-degree-of-freedom loading has to be applied accurately on the specimen; force control is necessary in the linear range for the stiff axial degrees-of-freedom and has to be combined with a displacement-based finite element model; and a mode-switch algorithm must be implemented to ensure accurate control after initiation of the specimen failure. The current paper will describe strategies to overcome the challenges described above and the development of a test setup to investigate and validate the application of hybrid simulation to the gravity load collapse of reinforced concrete frames. Validation will be achieved through a comparison with a shaking table test of a reinforced concrete frame (Elwood and Moehle, 2003).

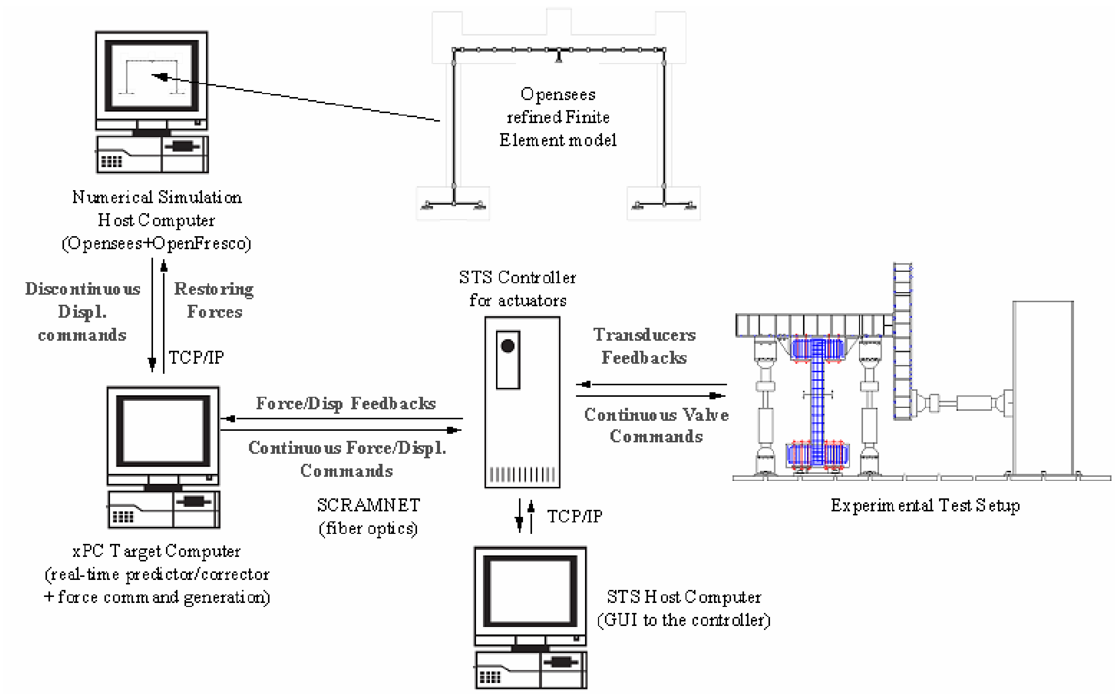

Figure 1. Global architecture of the UBC hybrid simulation setup.

Hybrid Simulation Global Architecture

Fig. 1 presents the global architecture of the hybrid simulation setup at the University of British Columbia (UBC). The finite element framework OpenSees (PEER, 2007) running on the *Numerical Simulation Host Computer* is used to solve for the displacement vector satisfying the governing equation of motion of the structural model at each time step. For the numerical substructures of the system, the restoring nodal forces corresponding to this displacement vector are obtained internally using the available nonlinear force-deformation models. On the other hand, for the experimental components of the model, the displacement vector is applied to the physical specimen by means of hydraulic actuators, and the corresponding restoring forces are directly obtained from the load cells and sent back to the computer program to populate the global restoring force vector necessary to solve for the displacements at the next time step. The software framework OpenFresco (Schellenberg et al., 2006) is used as the interface between the finite element software OpenSees and the actuator control system in the laboratory.

The *xPC Target Computer* runs an event-driven predictor/corrector application in the xPCtarget real-time environment (Mathworks, 2007). This predictor/corrector scheme was originally developed by Nakashima and Masaoka (1999) and subsequently refined by Mosqueda (2003) and Schellenberg (2005). The scheme uses polynomial Lagrange extrapolation and interpolation to generate continuous command signals for the actuators from the discontinuous displacement commands from OpenSees. The continuous command signals for the actuators are then written to a ScramNET (CWCEC, 2007) memory location and are thereby almost instantaneously available to the actuator-controller through a fiber-optic connection. A digital controller is then responsible for the application of these command signals on the specimen through the use of hydraulic actuators. The subsequent sections will describe OpenFresco and the predictor-corrector algorithm in more detail.

OpenFresco Hybrid Simulation Framework

So far no common framework for the development and deployment of hybrid simulation was available, and the past pseudo-dynamic experiments were performed using highly customized software implementations, which were dependent on the control system, the computational procedure and the site equipment used. This created tremendous difficulties adapting hybrid simulation to different structural problems and laboratories.

OpenFresco (Schellenberg et al., 2006) is an object-oriented software framework that enables researchers to carry out hybrid simulations of structural systems by acting as an interface between a finite element software and any laboratory testing equipment. No modification of the numerical simulation framework is needed, other than the addition of a generic finite element representing the physical element tested. With OpenFresco, the calls to obtain restoring forces and other parameters are made just like they would be made in any finite element analysis, except that they are executed physically somewhere in a lab by applying command displacements on a physical substructure. OpenFresco is independent of the finite element software used. However, for its ideal realization, the software must allow the addition of new elements. As such, Abaqus (Abaqus, 2006), LS-Dyna (Livermore Software, 2006), Matlab (Mathworks, 2007), OpenSees (PEER, 2007) and similar programs can in principle be used with OpenFresco.

OpenFresco is composed of four main abstract classes: *ExperimentalElement, ExperimentalSite*, *ExperimentalSetup* and *ExperimentalControl* that define the various operations, data, and relationships needed during a hybrid simulation to provide a bridge between a standard finite element analysis program and laboratory control and data acquisition systems, as schematically shown in Fig.2.

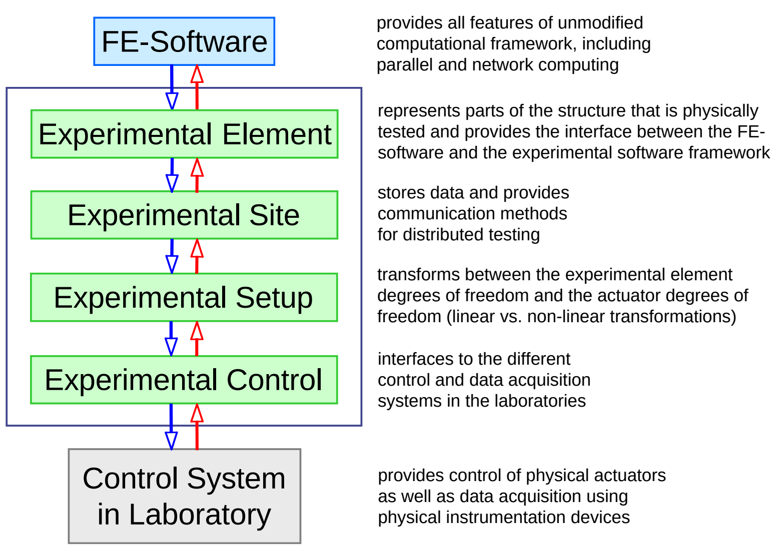

Figure 2. OpenFresco software framework components.

The *ExperimentalElement* object acts within the FE software to represent truss, beam, column, or other parts of the structure that are physically tested and provides the interface between the FE analysis core and the experimental software framework OpenFresco. The *ExperimentalSetup* class is responsible for transforming the degrees-of-freedom for each *ExperimentalElement* into actuator degrees-of-freedom, utilizing the linear/nonlinear geometry and kinematics of the loading and instrumentation system. The *ExperimentalControl* class is responsible for interfacing with the specific laboratory control and data acquisition systems. To enable geographically distributed testing, the *ExperimentalSite* class provides the tools for communicating between the experimental site (as a server) and the computational software (as a client). A *LocalExpSite* subclass is also available for a local (non-networked) implementation. A specific instance of the *ExperimentalSetup* class, *ESThreeActuatorsLshape*, was implemented for the proposed collapse test and will be described in detail in a subsequent section.

Event-driven Real-time Predictor/Corrector

An event-driven real-time predictor/corrector scheme is used to generate continuous command signals for the actuators, in order to suppress the force relaxation effects typical of the ramp-and-hold procedure and to also accommodate variable integration time steps (implicit integrators) or communication delays in geographically distributed testing. This real-time application can also be used to implement any control algorithm necessary for the test.

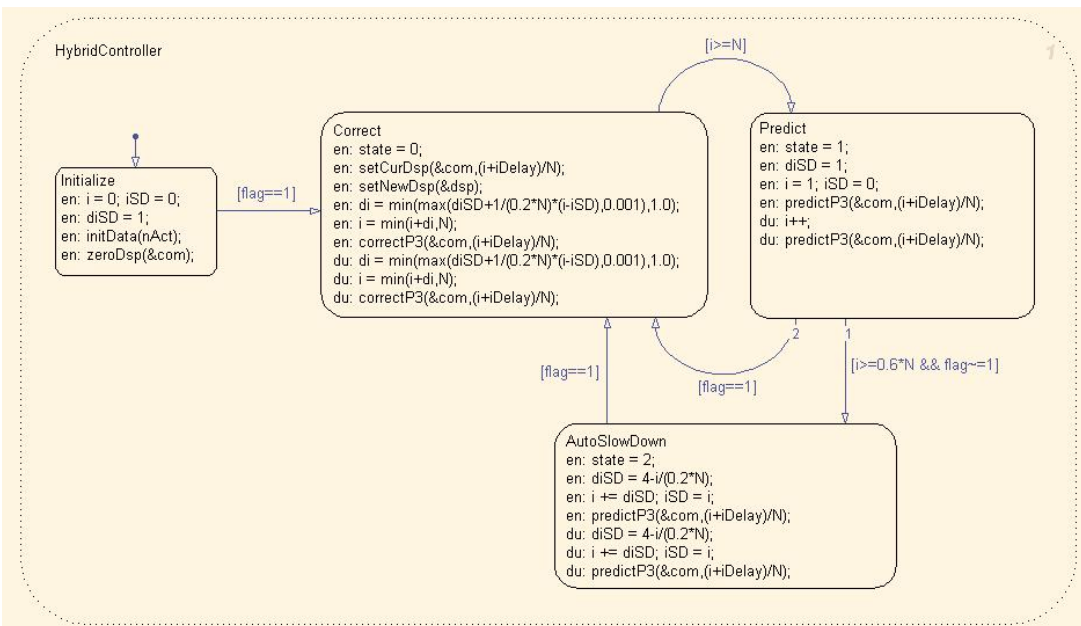

Figure 3. Event-driven real-time predictor/corrector (Schellenberg, 2005).

The real-time event-driven controller follows the procedure explained hereafter (based on Mosqueda, 2003):

- after reaching the target displacements/forces from the previous step, the actuators are kept in motion by predicting a command signal based on Lagrange polynomial interpolation of the previous target displacement values (*predictor mode*). Meanwhile, the finite element software is carrying out computations for the next target displacement.
- when the integration task is over, the new target displacement is received by the predictor-corrector which switches to the *corrector mode*: using Lagrange polynomial interpolation, the algorithm corrects the path of the actuators in order to reach the target value at the end of the simulation time step.
- if the integration or internet communication task lasts too long, the actuators could deviate

substantially from the intended trajectory and overshoot the next target displacement. That's why the algorithm switches to an *AutoSlowDown mode* when the prediction phase exceeds a given portion of the simulation time step. In this case, the motion of the actuators is smoothly slowed down until the next target displacement is received from the finite element software.

Modifications of this real-time controller scheme were performed to address the issues of force command generation and control-mode switch, and will be presented in a subsequent section. More detailed information on the event-driven predictor/controller can be found in Mosqueda (2003).

Test Setup for the Hybrid Simulation of Gravity Load Collapse of RC Frames

As mentioned in the introduction, using hybrid simulation to assess the collapse potential of structural systems presents many advantages compared to traditional experimental testing methods. However, solution strategies have to be defined to overcome the challenges raised by the use of this advanced testing method. Before using the test data to investigate the collapse mechanism of reinforced concrete frames, a validation phase is necessary to demonstrate the capacity of hybrid simulation to accurately simulate the dynamic behavior of a complex structural system. To achieve this objective, a hybrid simulation test setup was designed to reproduce existing shaking table tests of reinforced concrete frames (Elwood and Moehle, 2003).

Shake Table Test Specimens

The reference test specimen (Elwood and Moehle, 2003) consisted of a three-column frame with a shear-critical center column (Fig. 4), designed to achieve shear and possibly axial failure of the center column, yielding of the outside columns prior to failure of the center column, as well as, controlled transfer of loads from the wide beam to the columns. Two specimens, differing only by the axial stress on the center column (axial load of $0.10f'_cA_g$ and $0.24f'_cA_g$), were subjected to one horizontal component from a scaled ground motion recorded during the 1985 Chile earthquake.

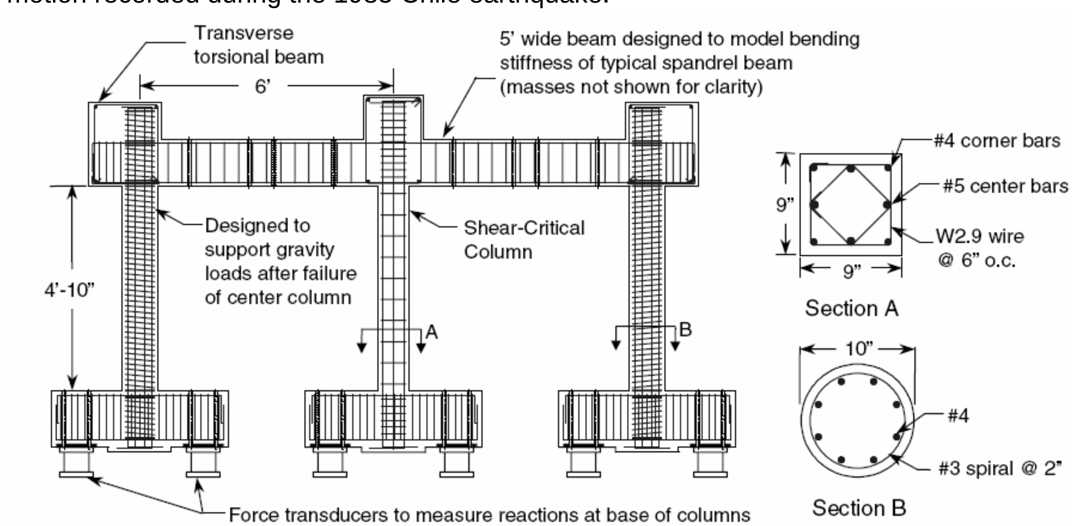

Figure 4. Shaking table test specimens (Elwood and Moehle, 2003).

Test results present a ductile behaviour for the outside columns with stiffness degradation, whereas the center columns suffer shear failure, followed by an axial-load failure for the second specimen (axial load of $0.24f'_cA_g$). The response for the center column during axial-load failure demonstrated that axial strength degradation may occur as a result of two possible mechanisms: sliding along a diagonal shear-failure plane when drift demands exceed a specific limit; and grinding down of the failure plane with repeated cycles. One goal of the hybrid test design described below is to try to reproduce these two mechanisms using hybrid simulation.

Hybrid Simulation Test Setup

One advantage of the concept of sub-structuring in hybrid simulation is that the parts of the structure whose behavior is efficiently captured by an analytical model can be simulated numerically in a finite element software, while the components difficult to model numerically – e.g. portions having a complex non-linear behavior – will be physically tested in the laboratory. Results from nonlinear analytical models (Elwood and Moehle, 2003) demonstrated that the behavior of the ductile outside columns as well as their footings and the top beam of the two-bay frame can be effectively captured by a refined nonlinear model in OpenSees. Being the critical component of the structure, the center column would still be physically tested through the use of a three-actuator dynamic test setup able to reproduce faithfully the loading imposed on the member during the seismic excitation of the whole structure (see Fig.5a).

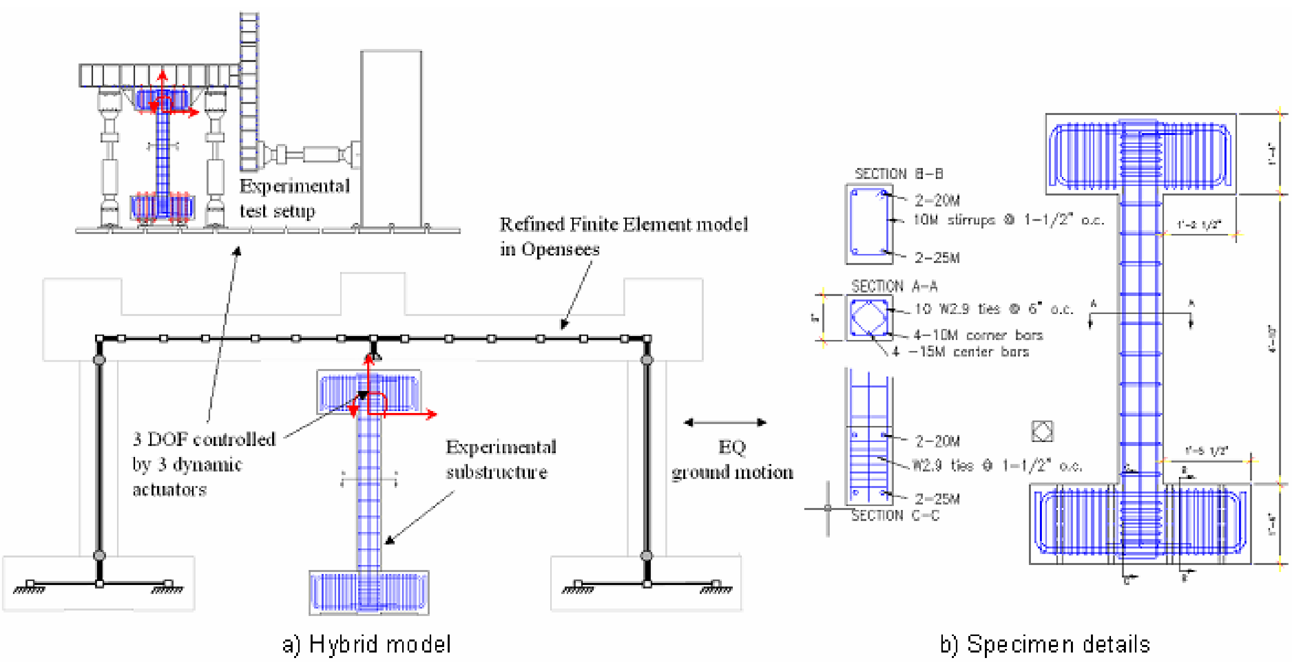

Figure 5. Hybrid simulation test setup with sub-structuring.

The physical substructure consists of a shear-critical column and footing similar to those tested by Elwood and Moehle (2003), topped by a stiff beam portion in order to be able to apply accurately the loading experienced by the member and also allow for the slip of longitudinal reinforcement at the top joint. Reinforcement details (see Fig. 5b) in the column were chosen to be as close as possible to Elwood and Moehle's despite the conversion from imperial to metric bar sizes.

Loading of the specimen is applied by three dynamic actuators controlled in displacement or force, according to the three-degree-of-freedom displacement commands generated by the OpenSees numerical model.

OpenSees Finite Element Model

The layout of the nodes and elements for the analytical model is shown in Fig. 6. The beams as well as the footings are modeled as linear-elastic, whereas nonlinear fiber beam-column elements are used to model the ductile outside columns. These nonlinear beam-column elements are based on the flexibility method (de Souza, 2000) and use fiber sections with confined and unconfined concrete models and a

Clough-type hysteretic model for the reinforcement. Zero-length sections are located at the extremities of each outside column to account for the slip of the longitudinal bars from the footings and beam, and an experimental beam-column element represents the center column and its footing.

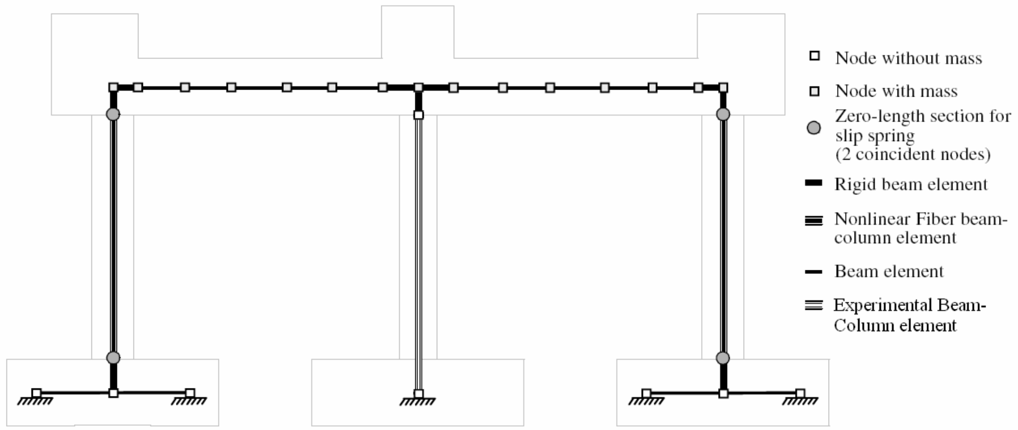

Figure 6. OpenSees finite element model.

Experimental Setup ThreeActuatorsLshape

To illustrate the OpenFresco *ExperimentalSetup* class, the *ESThreeActuatorsLshape* object developed for the specific three-actuator loading configuration of the test is presented in this section. The *ESThreeActuatorsLshape* object is responsible for transforming the beam-column element degrees-of-freedom into actuator displacements (Fig. 7).

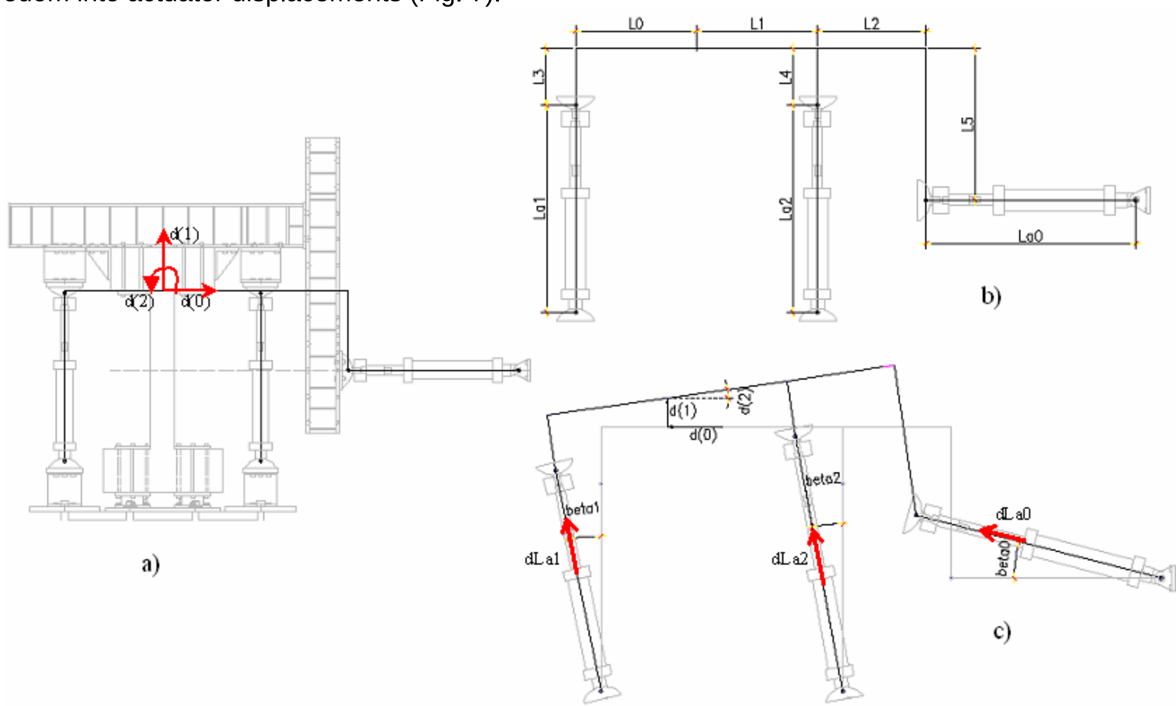

Figure 7. OpenFresco Experimental Setup *ThreeActuatorsLshape:* a) experimental setup; b) initial configuration; c) large displacements.

In the case of large displacements (Fig. 7c), the accurate application of the element DOF commands (***d***) through actuator displacements (***dLa***) implies considering the nonlinear geometry and kinematics of the configuration. This is achieved through trigonometric transformations on the command side, where ***dLa*** is a nonlinear function of ***d***. As a result, no closed-form solution is available on the data aquisition side, and a Newton-Raphson algorithm is used to solve for ***d***.

Iterative Force Command Generation and Force/Displacement Control-mode Switch

The high axial stiffness of the reinforced concrete specimen implies that the vertical actuators be acting in force control to limit inaccuracies in the application of the DOF commands. For this reason, an iterative algorithm (Fig. 8) was implemented within the event-driven real-time controller (Fig. 3) to generate continuous force commands for the vertical actuators. These force commands are based on the displacement commands from OpenSees, the measured displacements and the effective stiffness of the specimen which is updated at the controller at a rate of 1024Hz.

However, the vertical actuators can only be in force control while the specimen is in its linear range: displacement control is mandatory as soon as the specimen starts experiencing significant stiffness degradation, in order to avoid acceleration of the loading frame and subsequent crushing of the specimen if kept under force control. For this reason, a mode switch algorithm has been implemented to monitor the effective stiffness of the specimen and switch the vertical actuators from force to displacement control as soon as the effective stiffness goes under a predefined threshold.

In the linear range of the specimen, force commands are generated according to Equation 1:

$$f_{j+1} = f_j + K_j \cdot \frac{d_{target} - d_j}{M - j} \quad \text{with} \quad K_j = \frac{f_j - f_{j-1}}{d_j - d_{j-1}} \tag{1}$$

where $j = 0..M-1$ is the iteration index, K_j is the secant stiffness based on the displacement and force feedbacks of the previous iterations, f_j and d_j are the displacement and force measured at the end of the previous iteration j, and M is the fixed number of iterations to reach – in force control – the target displacement d_{target} computed by the predictor/corrector based on the displacement command from OpenSees.

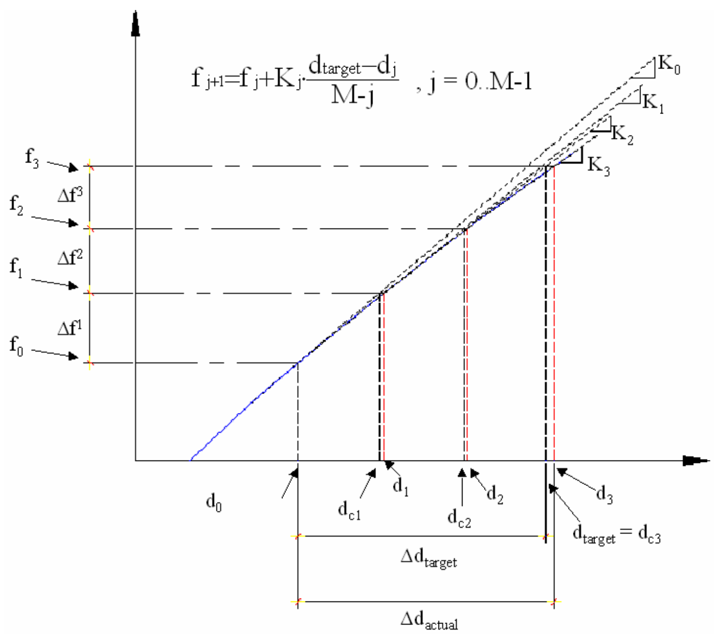

Figure 8. Iterative algorithm for the generation of continuous force commands (M=3, i.e. 3 iterations)
(d_{cj} is the target displacement that would be reached without stiffness changes, d_j is the actual displacement).

Within each substep of the predictor/corrector algorithm, M subiterations are performed to reach the target displacement d_{target} with the vertical actuators in force control. The force commands f_{j+1} are issued every 1/1024s. Note that the secant stiffness used in the computation corresponds to the state of the specimen during the previous iteration (1/1024s earlier), consequently the displacement d_M reached at the end of the iterations may be slightly different from the command displacement, d_{target}, if the specimen experienced changes in stiffness during the iterations. In the example presented in Fig. 8, the stiffness of the specimen has decreased by 15% at the end of the iteration process, which leads to a displacement d_3 which is 3% larger than the target displacement, d_{target}. However, this algorithm is only used in the linear range of the specimen, so that the inaccuracies that may result from a change in the actual stiffness are small compared to the inaccuracies that would result from the use of displacement control on a stiff specimen.

Conclusions

The lack of a flexible software framework for hybrid simulation was up to now a major drawback in the development of this advanced testing method. The recently developed open-source software for hybrid simulation OpenFresco provides a robust, transparent, adaptable and easily extensible framework that links any finite element software to any laboratory testing equipment. The combination of OpenFresco with a refined finite element model in OpenSees, in addition to an event-driven predictor/corrector incorporating algorithms to generate force commands and to switch control modes, enables the current study to push the boundaries of hybrid simulation by enabling the experimental testing of a complex reinforced concrete model beyond shear and axial failure of a single component. These recent developments in the field of hybrid testing offer new possibilities for the evaluation of complex structures, especially in the field of simulation of collapse/failure. Ongoing research by the authors will evaluate the ability of the hybrid simulation experimental setup described herein to reproduce shake table tests on the gravity load collapse of reinforced concrete frames.

Acknowledgments

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References

Comartin, C.D., 2001. PBEE Needs, Buildings Perspective : Critical Needs throughout the Performance Spectrum, *2001 PEER Annual Meeting*¸Oakland, California.

Elwood, K.J. and Moehle, J.P., 2003. Shake Table Tests and Analytical Studies on the Gravity Load Collapse of Reinforced Concrete Frames, *PEER report 2003/01,* Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Ghannoum, W.M., Shin, Y.B. and Moehle, J.P., 2005. Collapse Tests of Lighlty Confined Reinforced Concrete Columns and Frames, *Proceedings of the First NEES/E-Defense Workshop on Collapse Simulation of Reinforced Concrete Building Structures*, *PEER report 2005/10,* Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Inoue, N., Inai, E., Wada, A., Kuramoto, H., Fujimoto, I., and Iiba, M., 2000. A Shaking Table Test of Reinforced Concrete Frames Designed Under Old Seismic Regulations in Japan, *Proceedings of the 12th World Conference on Earthquake Engineering,* New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 1783.

Mathworks, 2007. The MathWorks - xPC Target - Perform real-time rapid prototyping and hardware-in-the-loop simulation using PC hardware, http://www.mathworks.com/products/xpctarget/, 02/27/2007.

Minowa, C., Ogawa, N., Hayashida, T., Kogoma, I., and Okada, T., 1995. Dynamic and Static Collapse of Reinforced-Concrete Columns, *Nuclear Engineering and Design*, Vol. 156, pp. 269-276.

Mosqueda, G., 2003. Continuous Hybrid Simulation with Geographically Distributed Substructures, *Ph.D. Dissertation*, University of California, Berkeley

Nakashima, M. and Masaoka N., 1999. Real-time on-line test for MDOF systems. *Earthquake Engineering & Structural Dynamics*, **28**(4), p. 393-420.

Pacific Earthquake Engineering Research Center, 2007. Open System for Earthquake Engineering Simulation - Home Page, http://opensees.berkeley.edu, 02/27/2007.

Schellenberg, A., Kim H.K., Takahashi Y., Fenves G.L., and Mahin S.A., 2006. *OpenFresco Framework for Hybrid Simulation: Installation and Example Guide*, available through NEESit.

Schellenberg, A., 2005. Predictor-Corrector Algorithms for Event-Driven Controllers in Hybrid Simulation, *CE 299 Report*, University of California, Berkeley

Sezen, H., 2002. Seismic Response and Modeling of Reinforced Concrete Building Columns, *Ph.D. Dissertation*, University of California, Berkeley

de Souza, R.M., 2000. Force-based Finite Element for Large Displacement Inelastic Analysis of Frames, *Ph.D. Dissertation*, University of California, Berkeley.

Takahashi, Y. and Fenves, G., 2005. Software Framework for Distributed Experimental-Computational Simulation of Structural Systems, *Earthquake Engineering and Structural Dynamics*, published online on Wiley InterScience (www.interscience.wiley.com) DOI: 10.1002/eqe.518