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Review Article

Seismic Hybrid Simulation of Stiff Structures: Overview and Current Advances

Stathis N. Bousias

Department of Civil Engineering, University of Patras, 26504 Patras, Greece

Correspondence should be addressed to Stathis N. Bousias; sbousias@upatras.gr

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Advances in the area of structural testing have in recent years led to hybrid simulation, that is, the advanced structural experimental method that encompasses the traditional pseudodynamic testing method and relies on substructuring to offer the advantage of combining the actual experimental testing of selected parts of the structure to the numerical treatment of the rest. The experimental part usually involves simplified test setups and structural elements with few degrees of freedom. Thus, issues of cross-coupling present in testing MDOF structures have not been treated adequately so far. In addition, it has been realized that when it comes to testing very stiff structures, in which the above phenomena are accentuated, further problems arise in relation to the quality of actuator control (accuracy of imposed displacements and stability of the test process). Few studies have focused on these issues, thus necessitating more work in the future. The present study provides an overview of the approaches that have been adopted so far, reports on recent advancements, and raises the points in which more research is needed.

1. Introduction

Extensive research and application of the pseudodynamic testing method in the 35 years that followed its inception, the "computer-actuator online testing method" [1, 2], have not only established it as one of the "standard" methods for seismic testing, but its application has also been extended towards new areas. By leveraging equipment commonly found at structural laboratories, the method has proven very competitive against costly shaking table testing, especially regarding the simulation of full-scale structures that respond in the nonlinear regime. With the exception, maybe, of its application to testing rate-dependent materials and distributed-mass systems, many of its initial weaknesses have been successfully treated: implicit or explicit/implicit methods for the integration of the equation of motion in time are now available, experimental errors have been minimized/compensated thanks to the deployment of high accuracy sensors or compensation techniques, and the staggered, ramp-hold-type, application of target displacements that introduced force-relaxation issues has been substituted by the continuous movement of the actuators (continuous pseudodynamic testing method).

Furthermore, the extension of the method based on the concept of substructuring (i.e., the discretization of selected parts of the structure under test into actively interacting physical and numerical models (substructures)) forming a, so-called, "hybrid model" has resulted in creating a valuable tool for testing structures of such large size that could not be accommodated in present-day laboratories (e.g., bridges). It was exactly the concept of substructuring that opened up new possibilities and allowed innovative applications of the method, such as the geographically distributed substructured tests and the real-time substructured tests. New, open-source type, software tools have also been developed to facilitate the coordination and execution of distributed hybrid simulations. To encompass these developments and the fact that while in traditional pseudodynamic tests the inertia effects are treated within the analytical part, while in real-time substructured tests part of the inertia is offered by the physical subsystem, the term "hybrid simulation" was coined in recent years, principally through the Network for Earthquake Engineering Simulation (NEES, http://www.nees.org).

Notwithstanding the progress achieved, one cannot claim that hybrid simulation has overcome all difficulties and can be routinely used to perform seismic testing of full-scale structures. Open issues that remain to be treated include

(i) multiactuator substructured tests,

(ii) hybrid real-time simulation,

(iii) testing very stiff structures,

(iv) geographically distributed tests on MDOF structures,

(v) transparency and reliability of distributed-testing employing existing platforms.

Testing stiff structures is an area pinpointed as one necessitating further work, especially regarding the issue of force-controlled testing. The present paper provides an overview of the current state in the area and looks into new methods proposed for the hybrid simulation of stiff structures.

2. Hybrid Simulation of Stiff Structures: Issues and Approaches

Amongst the structural elements/systems tested through hybrid simulation, those characterized by increased stiffness form a special class, due to a number of difficulties associated with both their numerical and experimental treatment.

One of the first and well-known issues encountered in simulation algorithms performing the numerical integration of the equations of motion of stiff structures is that the explicit time integration methods yield very strict (small-sized) time integration interval requirements, as determined by the high value of the highest structural natural frequency. Thus, either unconditionally stable (implicit) schemes or mixed ones (explicit scheme for the experimental substructure and implicit scheme for the physical substructure) must be employed. Nevertheless, even if an acceptably small integration time step size can be defined, the resulting displacement increments are very difficult—from the standpoint of control—to apply at the controlled DOFs both because of their size (being sometimes smaller than the resolution of the transducer used for the displacement-feedback signal) and of the associated measurement errors.

If the structure under test is a multi-degree-of-freedom one, then additional difficulties arise from the tight cross coupling of the DOFs. If a very stiff structure is assumed with a number of displacement-controlled actuators being firmly attached on the active structural degrees of freedom, then any individual actuator adjustment (due to a command signal or due to a minimal movement around its point of equilibrium with nil input signal) is instantly transferred through the stiff structure and sensed by the stiffly coupled DOFs and, hence, from the actuators. This minimal action is perceived by each of the latter as an external action attempting to modify their own state of equilibrium (note: the actuators are controlled in displacement) and, thus, they react striving to maintain their position. The resulting reaction forces are of very high magnitude due to the high structural stiffness. A possible workaround of the actuator cross coupling problem would be to operate them under force control (at least for the part of the response in which the specimen is stiff), provided that the time-history variation of forces to be applied at each active DOF is known beforehand and operation of actuators in force is as reliable as under displacement.

An idea for facing tight stability conditions, small displacement increments and actuator cross coupling phenomena, is to provide additional flexibility in the force-transfer chain from the actuator to the structure to produce an *amplification of the command displacement signal* before it is being sent to the (displacement-controlled) actuator. Instead of firmly fixing the actuator end to the structure under test, a linear elastic flexible element is provided between the actuator and the structure. This additional flexible element can be realized as in Seible et al. [3] who used elastomeric pads as the flexible link to transfer the intended actuator force (actuator is in displacement-control mode) to a 5-story shear wall structure (Figure 1). The pads, conceived not only for *displacement amplification* but also for bypassing the problem of tight coupling between actuators attached on the active DOFs, were inserted between the force-transfer steel beams attached to the actuator and the floor slabs of the structure and subjected to normal forces via prestressing bars. It was proved that, by selecting low-stiffness elastomeric pads, the accuracy in imposing the calculated target structural displacements is indeed better than the actuator precision. The proposed methodology (termed "soft coupling") was applied within the classic pseudodynamic method and a displacement-based integration algorithm. However, it resulted in complications in the control algorithm: an iterative procedure had to be employed seeking the appropriate displacement command signals to the actuators that would yield the intended (calculated) structural displacements on the specimen (Generated Sequential Displacement procedure—GSD). Consequently, apart from the questions raised about the linearity of response of the elastomeric pads, their connection to the structure in the presence of high amplitude loads and the stroke capacity of the actuators to apply the required increased displacements (especially when it comes to the soft state of response of the tested structure), the addition of an iterative procedure in the control loop further complicates the solution proposed.

A similar idea was employed by Sivaselvan et al. [4], with the difference being that in their implementation the reference quantity is the force to be applied and the actuator control loop is based on displacement. They employed the concept of "added compliance" to achieve high quality *dynamic force control* for the needs of real-time hybrid testing. For a single-degree-of-freedom system and with a known force to be applied by a displacement-controlled actuator, they employed a spring between the actuator and the structural mass (Figure 2) to play the role of the flexible link (added compliance). The strategy, coupled with displacement feed-forward compensation, appeared adequate for dynamic force control of the single, low mass (77.27 kg) structure, but it avoids sending directly forces to the actuator and has not been employed for testing MDOF stiff structures also presenting the known coupling effects.

3. Force-Control Hybrid Simulation Problems

Past studies [3–7] have shown that force—instead of the displacement—should be a more appropriate command

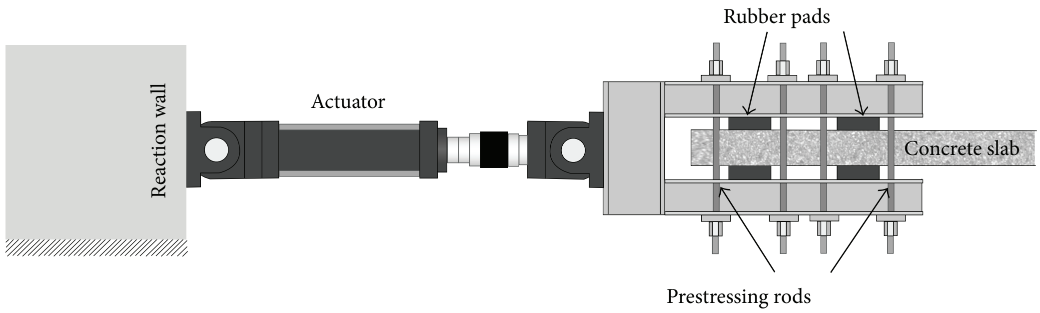


FIGURE 1: Concept of soft coupling [3].

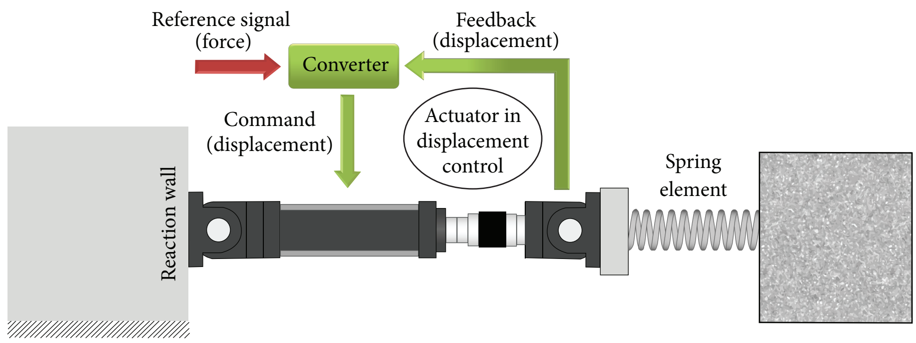


FIGURE 2: Concept of "added compliance" by Sivaselvan et al. [4].

signal for the actuator during the part of the response in which the specimen is stiff (for the softening branch of the specimen response, though control has to be appropriately switched to displacement to avoid instability). For employing actuators in force control the following conditions need to be fulfilled:

(i) actuators operate in force control applying calculated forces with minimal error;

(ii) forces to be applied are known a priori, either through a force-based formulation of the hybrid simulation algorithm (currently not available), or through a stiffness-based modification of calculated displacements, in case a displacement-based formulation is employed in the finite element analysis software.

Regarding the first of the conditions above, force is proved to be difficult to use for closing the servo loop, due to a number of reasons. At first, assume that it is possible for the finite element analysis software to provide the forces to be applied at the controlled DOFs or that calculated displacements are (somehow) translated into reference forces. The force signal measured by the actuator load cell and subsequently used as the feedback signal in the control algorithm is not noise-free. A number of sources contribute to the low quality of the force signal (friction, break-away forces on piston seals, and stick slip) leading to a degraded actuator performance. It is also obvious that tuning of a controller which commands an actuator in force is stiffness-dependent and requires the availability of a very stiff elastic test piece (other than that used for the purposes of the research). Even if this condition is satisfied, the results are valid only for that stiffness the controller was tuned for and will suffer from loss of smoothness if the specimen under study is characterized by changing stiffness.

Another difficulty for performing force-controlled hybrid tests stems from the fact that even if forces could be determined via a force-based integration scheme, they would be then expressed in the same coordinate system in which equations have been formulated, that is, the global coordinate system. However, actuators can realize command forces (and displacements) only along their longitudinal axis, with the latter not necessarily being aligned to any of the axes of the global coordinate system during a test. It is obvious that a transformation is needed in this case, similar to that employed for obtaining the actuator displacement command from a displacement-based algorithm. While displacement transformation is straightforward using kinematic compatibility at nodes, when it comes to the case of forces, however, such transformation does not provide a unique solution for the forces to be applied to the physical (sub)structure.

An even harder problem to face is the control of the actuators themselves in force mode. With the mechanical impedance of a system being defined as the ratio of the potential (e.g., force) at a point to the resulting velocity at that point, actuators (as velocity sources) are, by design, high impedance systems (mechanically stiff) offering good position control [4]. The high structural stiffness leads to the selection of a low proportional gain in the controller and with an increasing structure-to-actuator stiffness ratio the response is characterized by increasing risk of oscillatory nature, that is, instability (the poles of the system move closer and upwards to the imaginary axis).

The second condition for performing hybrid simulation via force-driven actuators, that is, that of the a priori availability of the time history of forces to be applied at each controlled DOF, requires the formulation of a *force-based* time integration algorithm for the hybrid simulation and the transformation of the forces determined in the global coordinate system to forces in the actuator reference system. Such formulation of general application is completely lacking, possibly because the development of schemes directly providing target forces is compromised by the difficulties arising in running the actuators under force control. The only effort towards a force-based method is that developed by Kim and reported by Whyte and Stojadinovic [8]; detailed information on the formulation is lacking and no data regarding actual application of this approach are available. With the exception of this study, the preferred testing methodology remains that of employing existing displacement-based formulations to determine target forces to be applied via displacement- or force-driven actuators. As finite element analysis codes and all currently available hybrid simulation platforms (Simcor, OpenFresco, Netslab, ISEE, etc.) are displacement-based, focus is directed on methods of obtaining target forces from calculated displacements. The available approaches falling in this category are known as compatibility methods for obtaining target forces and are summarized in Figure 3, with a more detailed description given in the following.

4. Target Force Determination

4.1. Stiffness-Based Approaches. These approaches comprise those by Pan et al. [9], Nakata et al. [10], Elkhoraibi and Mosalam [6], Igarashi et al. [5], Ahmadizadeh and Mosqueda [11], and Hung and El-Tawil [12]—all are based on the determination of the stiffness matrix to be used with displacements obtained from the time integration process to yield target forces.

Pan et al. [9] performed hybrid simulation on a base-isolated building by substructuring the isolators as physical specimens. Loading along the vertical direction was realized on the isolator by a force-control loop only for the stiff state of the isolator, that is, the compression, while for tension (soft state) the control switched to displacement. Vertical forces to be applied were determined from displacements via the elastic stiffness of the bearing. This defines also the main drawback of the method; that is, it is not valid for the case of nonlinear (and unknown) variation of stiffness.

Nakata et al. [10] studied the problem of concurrently controlling a number of actuators used to load specimens with prescribed target displacements and forces along different axes. As the servo loops of all actuators were closed with displacement feedback, a procedure was developed to derive displacement commands for the actuators in load-controlled axes. Specifically, the study examined the response of reinforced concrete columns under imposed cyclic lateral deformations at the presence of constant axial compression. In the load-controlled axis (direction in which a prescribed force should be achieved), the displacement command signal to the actuator during the ith iteration of step N is obtained by

$$u^{c}_{N(i)} = u^{c}_{N(i-1)} + G \cdot K_{N(i-1)} \left(f^{t}_{N} - f^{m}_{N(i-1)} \right), \tag{1}$$

where u^c represents the command displacement signal, G is a gain matrix, $K_{N(i-1)}$ is the updated stiffness after the $(i-1)$th iteration, f^t is the target force, and f^m is the measured force at $(i-1)$th iteration. After the ith iterative ramp is realized, displacements and forces are measured and their respective increments are determined:

$$\Delta u^{m}_{N(i)} = u^{m}_{N(i)} - u^{m}_{N(i-1)}, \qquad \Delta f^{m}_{N(i)} = f^{m}_{N(i)} - f^{m}_{N(i-1)}. \tag{2}$$

After the ith iterative ramp, the secant stiffness is estimated via the Broyden update of the Jacobian [13]:

$$K_{N(i)} = K_{N(i-1)} + \frac{\left(\Delta f^{m}_{N(i-1)} - K_{N(i-1)} \cdot \Delta u^{m}_{N(i)} \right) \left(\Delta u^{m}_{N(i)} \right)^{T}}{\left\| \Delta u^{m}_{N(i)} \right\|^{2}}, \tag{3}$$

where u^m represents the measured displacement after the ith iterative ramp. Convergence to the prescribed force f^{targ}_{N} is achieved when

$$\left| f^{\text{targ}}_{N} - f^{\text{meas}}_{N(i-1)} \right| < \text{tolerance}. \tag{4}$$

The method has been successfully incorporated into the control software of the NEES MUST-SIM facility at UIUC [10] to cope with issues related to their mixed displacement-load-controlled specialized equipment.

Another secant-stiffness-based methodology yielding target forces is that by Elkhoraibi and Mosalam [6]. For a system with *uncoupled* DOFs, secant stiffness at each DOF was determined directly using the incremental measured force and displacement during the iterations within a time step $(n+1)$ and the respective converged values at the end of previous time step (n). To overcome the problems of the resolution of measuring sensors and random noise in measurements, they used the average of a number (100) of consecutive force/displacement measurements to calculate the average stiffness. They reported satisfactory results, but the method has not been further verified for stiff MDOF structures presenting coupling between the degrees of freedom.

The approaches by Pan et al. [9], Nakata et al. [10], and Elkhoraibi and Mosalam [6] are secant-stiffness-based as opposed to those by Igarashi et al. [5], Ahmadizadeh and Mosqueda [11], and Hung and El-Tawil [12] which target to determine the tangent stiffness. To perform hybrid simulation on a stiff 5-story full-scale building Igarashi et al. [5] used displacement feedback for the servo loop of the actuators and the Broyden-Fletcher-Goldfarb-Shanno (BFGS) method for tangent stiffness updating during the test. At step n, the incremental displacement and force measured at each DOF are related to the tangent stiffness matrix K^{act}_{m} via

$$\Delta \hat{f}_{n} = K^{\text{act}}_{n} \Delta \hat{u}_{n}. \tag{5}$$

An incremental stiffness is determined by the algorithm to update the stiffness matrix and a parameter representing the

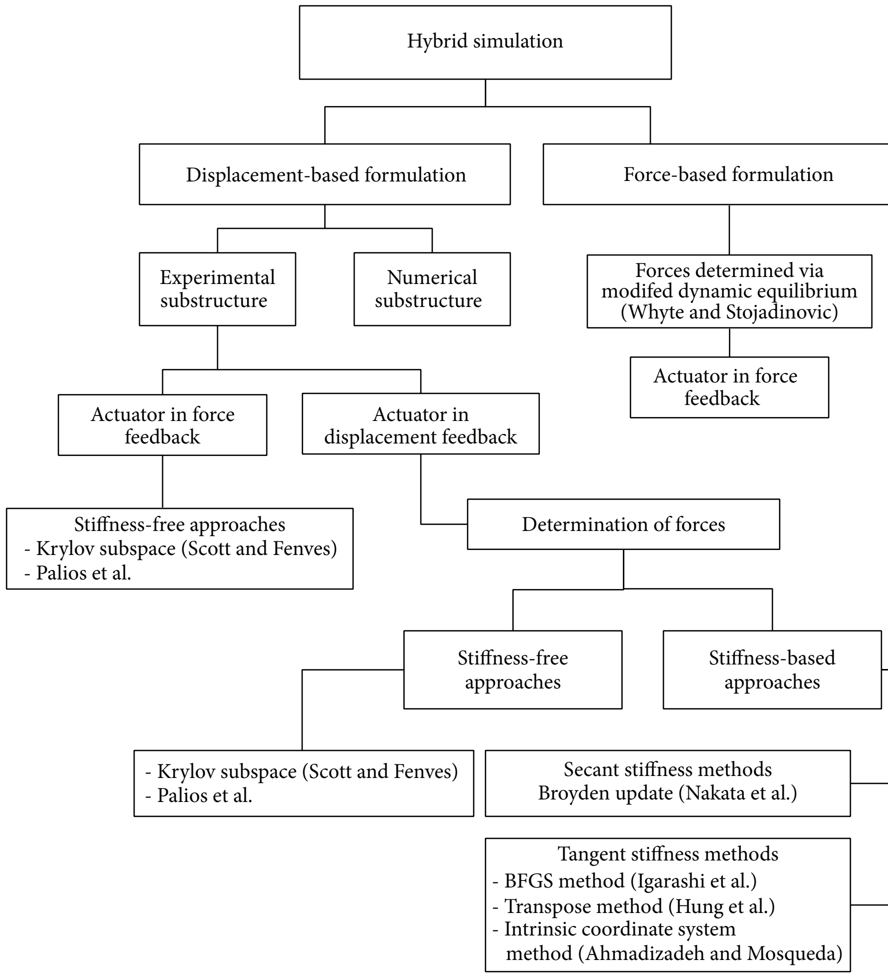


Figure 3: Force determination methods in displacement-based hybrid simulation.

fidelity of the testing system is employed, so that spurious updating of stiffness is avoided. The incremental stiffness is obtained as

$$\begin{aligned}
\Delta K1_n^{\text{act}} &= \left[1 + \frac{\Delta\widehat{u}_n^T \cdot K_o^{\text{act}} \cdot \Delta\widehat{u}_n}{\Delta f_n^T \cdot \Delta\widehat{u}_n}\right] \frac{\Delta\widehat{f}_n \cdot \Delta\widehat{f}_n^T}{\Delta\widehat{f}_n^T \cdot \Delta\widehat{u}_n} \\
&\quad - \frac{\Delta\widehat{f}_n \cdot \Delta\widehat{u}_n^T \cdot K_o^{\text{act}}}{\Delta f_n^T \cdot \Delta\widehat{u}_n} - \frac{K_o^{\text{act}} \cdot \Delta\widehat{u}_n \cdot \Delta\widehat{f}_n^T}{\Delta f_n^T \cdot \Delta\widehat{u}_n}, \\
\Delta K2_n^{\text{act}} &= \left[1 + \frac{\Delta\widehat{u}_n^T \cdot K_n^{\text{act}} \cdot \Delta\widehat{u}_n}{\Delta f_n^T \cdot \Delta\widehat{u}_n}\right] \frac{\Delta\widehat{f}_n \cdot \Delta\widehat{f}_n^T}{\Delta\widehat{f}_n^T \cdot \Delta\widehat{u}_n} \\
&\quad - \frac{\Delta\widehat{f}_n \cdot \Delta\widehat{u}_n^T \cdot K_n^{\text{act}}}{\Delta f_n^T \cdot \Delta\widehat{u}_n} - \frac{K_n^{\text{act}} \cdot \Delta\widehat{u}_n \cdot \Delta\widehat{f}_n^T}{\Delta f_n^T \cdot \Delta\widehat{u}_n}, \\
\widehat{K}_{n+1}^{\text{act}} &= K_o^{\text{act}} + \Delta K1_n^{\text{act}}, \quad \text{if } \left\|\Delta K1_n^{\text{act}}\right\| < \left\|\Delta K2_n^{\text{act}}\right\|, \\
\widehat{K}_{n+1}^{\text{act}} &= K_o^{\text{act}} + \Delta K2_n^{\text{act}}, \quad \text{if } \left\|\Delta K1_n^{\text{act}}\right\| > \left\|\Delta K2_n^{\text{act}}\right\|.
\end{aligned} \tag{6}$$

As has been shown by Ahmadizadeh and Mosqueda [11], the Broyden update approach may result in a nonsymmetric or nonpositive definite stiffness matrix and with a slow stiffness update rate, while the BFGS method suffers from considerable distortions being introduced by noise. In general, results from simulations indicated that both the Broyden and the BFGS methods do not exhibit sufficient accuracy over that resulting from the use of the initial stiffness matrix. To that end, Ahmadizadeh and Mosqueda [11] offered a different approach in estimating the tangent stiffness matrix. They use the notion of "*intrinsic coordinate system*" (determined for each experimental setup and specimen) to express the measured displacements/forces (in actuator coordinate system) and ultimately obtain a (diagonal) stiffness matrix in the intrinsic coordinate system, P_n:

$$\begin{aligned}
\Delta u_n^P &= T_P \, \Delta\widehat{u}_n^{\text{act}}, \\
\Delta f_n^P &= P_n + T_P \left(K_{n-1}^{\text{act}}\right)^{-1} \Delta\widehat{f}_n, \\
K_n^{\text{act}} &= T_P^T P_n T_P.
\end{aligned} \tag{7}$$

The latter is then expressed in the global coordinate system through an appropriate transformation. Although the authors provided an example of application of the method on a simple, two-DOF specimen, the procedure may become more intricate for more complex setups.

Based on small-scale tests on a simplified setup (μNEES), it was shown that the method offers a far better estimation of the tangent stiffness from the point of view of accuracy compared to the Broyden or the BFGS approach. To present, the method has not been verified for testing stiff MDOF structures.

Although not developed for hybrid simulation of stiff structures but rather to improve the integration schemes (as with [11]), the methodology by Hung and El-Tawil [12] is a nonsecant approach for determining the tangent stiffness matrix of MDOF structures. It employs past m-steps during the test to formulate a relationship between incremental forces and displacements, based on the assumption that the stiffness does not change substantially within a number of m previous steps (m is defined by the user, but in general $m \geq$ DOF). A unique solution is obtained if m is equal to the number of DOFs, while least-squares approximation must be employed when $m >$ nDOFs. The method has been examined only numerically (no physical testing was performed) and for structures with hardening response.

4.2. Stiffness-Free Methods. As stiffness-based methods suffer from noise in the measuring sensors causing contamination in force/displacement measurements and spurious updates of stiffness, alternative approaches have been investigated. Scott and Fenves [14] used a Krylov subspace as the basis for determining target forces from displacements available by the integration process. Nonetheless, the method uses the initial stiffness at some point of the process (or can employ tangent stiffness obtained by one of the previous methods). The method has been implemented in the OpenFresco platform [15] but no actual application has been reported.

The approach by Scott and Fenves [14] along with some of the tangent-stiffness-based approaches reported above has been implemented in OpenFresco by Kim et al. [15] and the μNEES experimental setup was used for verification and comparison. Indicative results seem to sustain that the BFGS method yields better results than those by the rest of the methods, as long as the controlling variable is not force. Nonetheless, the results of Ahmadizadeh and Mosqueda [11] obtained from the same test setup indicated that both BFGS and Broyden methods do not offer clear advantage over using the initial stiffness matrix, as far as accuracy is concerned.

A more recent, stiffness-free method, is that by Palios et al. [16]—the method strives to tackle concurrently two problems, that of determining the appropriate target force and that of actuator coupling effects. The method functions under the usual displacement-based formulation and is based on the use of two controllers per actuator, in an inner-outer loop configuration: the first controller is assigned with the conversion of target displacement into target force, while the second one is responsible for driving the actuator under force control. At each sampling time interval of the control system, new target displacement increments are calculated by the integration scheme and sent to the first controller. The displacement-feedback signal is compared to the target displacement and the error is used within the first controller to produce a signal that is sent as command to the second controller. As the latter is the one actually driving the actuator in force, the signal received from the first controller is scaled so that its maximum value corresponds to the full capacity of the actuator used. The resulting signal is the servovalve command to drive the actuator in force control. Although the method is the only one to have been applied for testing a very stiff reinforced concrete wall and shown to yield accurate results, further research regarding its stability limits is required.

4.3. Applications in Actual Testing. Most of the methods presented above have been applied to rather idealized specimens of few degrees of freedom, as focus was mainly on the development and analysis of the relevant methods. The few cases of actual application of seismic hybrid simulation to testing real-scale stiff structures are those by Seible et al. [3], Igarashi et al. [5], Whyte and Stojadinovic [8], and Palios et al. [16]. In the first two studies (the only ones on actual MDOF stiff structures) the tangent stiffness approach was used and while the experimental error (the difference between commanded and measured displacements) was shown to be within acceptable limits for the low excitation level tests, increasing seismic input level induced higher displacement error, owing to the nonlinearity of the soft coupling system. Several of the difficulties encountered in these tests due to the analog control system and the poor resolution of the displacement-feedback transducers are deemed to have been solved by the technological evolutions in the period that followed these tests.

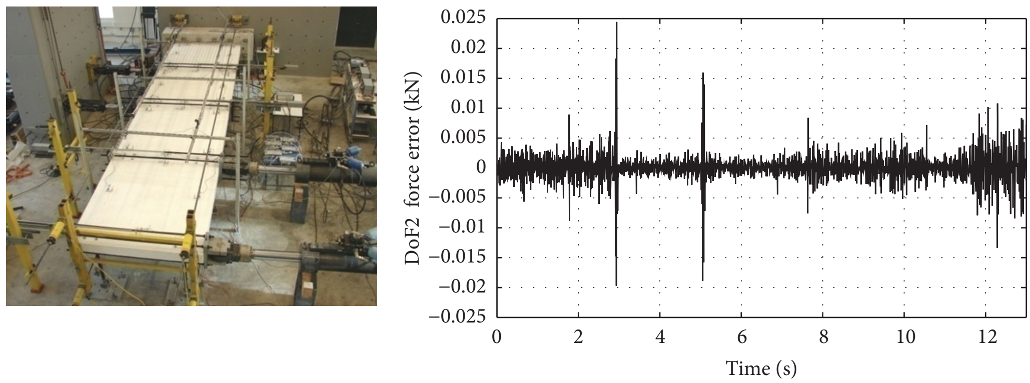
The physical components in the hybrid simulation tests performed by Whyte and Stojadinovic [8] were represented by squat shear walls subjected to seismic input of increasing level. The tests were actually performed under displacement-feedback control employing high-resolution digital displacement transducer. As the specimen comprised only one degree-of-freedom, no stiff coupling was present and the use of force control was not necessary. Accurate control was partially compromised by the equipment employed (slip in actuator clevis) and was solved introducing a special procedure (constant velocity control).

The approach by Nakata et al. [10] was employed by Hart et al. [17] in hybrid simulation testing of a series of three-story shear walls in 1 : 3 scale, via the secant-stiffness approach. The test results have shown that accurate response is obtained along the load-controlled axes of the specimen.

In the seismic hybrid simulation of four-story shear wall tests performed by Palios et al. [16] at a 3 : 4 scale (Figure 4), the dual controller approach was used with a target displacement resulting from a displacement-based formulation and the actuator control loop closing in force. Testing of this stiff specimen was performed with an accurate force control as evidenced by the negligible difference between target and measured forces (error) observed.

5. Conclusions

The objective of this study is to address the issue of testing very stiff structures within the context of seismic hybrid



(a) (b)

Figure 4: (a) Test setup and (b) force error in force-controlled actuator.

simulation. A number of currently employed methods were reviewed to identify their pros and cons. The common ground is that, while force should be the controlling variable of the actuator servo loop, it has not been so far possible to perform accurately controlled testing with actuators in force control. It is obvious that more effort is needed along this direction and investigation of alternatives within this particular application area, for both low and high force amplitude/frequency.

Regardless of the current difficulties in testing very stiff structures in control of force, the issue of how to obtain the forces to be applied from present-day integration schemes (which are all displacement-based) remains. The approaches in this area can be broadly categorized as stiffness-based or stiffness-free, with the majority falling into the first category. The fact that these methods have been primarily developed for improving the time integration schemes and not so much for being used for force-controlled testing has not allowed the thorough investigation of their potential on actual stiff structures. Another point requiring further work regards the development of more stiffness-free methods, as a way to overcome problems associated with measurement errors that influence negatively all stiffness-based approaches.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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