Computational Structural Dynamics and Earthquake Engineering

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Chapter 15

Multi-resolution distributed FEA simulation of a 54-story RC building

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ABSTRACT: A recently developed analysis framework referred to as multi-resolution distributed finite element analysis, MDFEA, is presented in this chapter. The features of the new framework are demonstrated through the analysis of a complex 54-story reinforced concrete building. In this distributed analysis framework, the capabilities of a frame analysis tool, ZEUS-NL, and a continuum analysis tool, VecTor2, are combined using the 'simulation coordinator' program UI-SIMCOR. The static and dynamic responses of the building are predicted using MDFEA and compared with those predicted by conventional frame analysis. The results of this comparison illustrate that frame analysis of high-rise building alone is inadequate to detect the effects of shear-flexure-axial interaction of reinforced concrete continuum members. The integrated MDFEA framework is generic, thus it enables the use of the best features of any number of computational tools so as to accurately and efficiently predict the inelastic static and dynamic response of complex structures subjected to extreme loads.

1 Introduction

The response of low-rise structures to earthquake loading has been extensively studied by employing advanced finite element analyses (FEA), quasi-static experiments, pseudo-dynamic (PSD) simulation of structural components and structural systems. It has also been investigated through shake table tests on models at different scales. On the contrary, reliable estimation of the structural capacity of complex high-rise reinforced concrete (RC) or composite systems under extreme loads has been hindered by the lack of suitable analysis software, computational capacity for refined model analysis, and the impracticality of experimental testing.

The response of complex high-rise buildings has principally been studied using simplified models. Usually wall systems are modeled using frame elements that do not fully account for the effects of shear on deformations and capacity, and the interaction between shear and flexure, as discussed by Ghobarah & Youssef (1999). The latter approach is inadequate since the failure mode of structural walls in high-rise buildings is frequently influenced and controlled by the effects of shear (Paulay & Priestley, 1992). In some instances, the critical components of structural systems have been analyzed using detailed continuum finite element models. However, in doing so, the boundary and loading conditions imposed on these models are typically idealized or estimated from separate coarse structural models. This non-interacting load and boundary conditions approach is also inadequate since the propagation of failure and redistribution of force demands between components cannot be accurately accounted for. While it may be possible to analyze an entire high-rise structure using detailed FEA, the computational demands of executing this analysis are enormous and render it impractical to conduct adequate parametric studies to account for the uncertainty on loading, modeling and inherent randomness in materials. Furthermore, such a detailed model is a non-starter for probabilistic assessment, where statistically-viable populations of response parameters are sought.

One effective and computationally efficient method to analyze large and complex structures would be to combine different modeling approaches, such as to model the most critical non-slender regions using continuum analysis and to model frames using fiber-based beam elements. Unfortunately, computation platforms seldom provide the most advanced modeling capabilities for all possible elements that would be best to use in the modeling of a complex structural system. The natural solution to this dilemma is to create an analysis framework in which different analysis programs could be combined in one integrated analysis where each program would be selected to make the best use of its merits. Such a framework is developed in this chapter.

The framework for multi-resolution distributed finite element analysis (MDFEA) proposed in this chapter is used to analyze a complex high-rise RC building. The structural walls of this building are modeled with concrete continuum elements while the frames are modeled with fiber-based beam-column elements. The two distinct applications are combined using the MDFEA framework in a step-by-step fashion in the time domain.

The chapter includes brief descriptions of the analysis modules, ZEUS-NL and VecTor2, as well as the simulation coordinator program UI-SIMCOR (Kwon et al., 2005), that was used to combine these analysis tools. The modeling details for the 54-story dual-system high-rise structure used as the reference implementation are presented including the techniques used to model the interface between the two structural models. The influence of different interface assumptions on predicted response is also examined. Using the selected interface boundary conditions, comprehensive comparisons between and discussions of the predicted static and dynamic responses by the MDFEA and by a conventional finite element analysis are presented.

2 Structural analysis software platforms

2.1 *ZEUS-NL: 3D frame FEM analysis software*

Fiber-based frame analysis is one of the most advanced methodologies to model the nonlinear behavior of beams and columns under combined axial and bending loads. The Mid-America Earthquake Center analysis environment ZEUS-NL (Elnashai et al., 2002), is a computational tool for the analysis of two and three dimensional frames. In ZEUS-NL, elements capable of modeling material and geometric nonlinearity are available. The forces and moments at a section are obtained by integrating the inelastic responses of individual fibers. The Eularian approach towards geometric nonlinearity is employed at the element level. Therefore, full account is taken of the spread of inelasticity along the member length and across the section depth as well as the effect of large member deformations. Since the sectional response is calculated at each loading step from inelastic material models that account for stiffness and strength degradation, there is no need to make assumptions on the moment-curvature response as commonly required by other analysis tools. In ZEUS-NL, conventional pushover, adaptive pushover, Eigen analysis, and dynamic analyses are available and they have been evaluated to be effective and accurately predicting the response of members and structural frames. ZEUS-NL was used to steer a full-scale 3D RC frame testing campaign, and the a priori predictions were shown to be accurate and representative of the subsequently undertaken pseudo-dynamic tests (Jeong & Elnashai, 2004a and 2004b). There have been many other verification examples. Due to scope of this paper, a reference is made to Elnashai et al. (2002) for further information.

2.2 *VecTor2: RC continuum FEM analysis software*

A concrete wall can be modeled as an orthotropic nonlinear inelastic continuum according to Modified Compression Field Theory (MCFT) (Vecchio & Collins, 1986). The MCFT is a rotating angle smeared cracking model that combines equilibrium, compatibility and constitutive relationships. It accounts for the effects of compression softening and tension stiffening. The method includes an evaluation of equilibrium at crack faces that is used to limit field stress levels. The MCFT assumes that the direction of principal stress coincides with that of principal strain. Vecchio (1990) proposed the algorithm for application of MCFT to concrete continuums subjected to plane stress conditions.

In this study, the nonlinear 2D continuum analysis tool VecTor2, Wong & Vecchio (2002), developed at the University of Toronto, is employed for modeling the bottom 10 stories of the structural walls. VecTor2 employs a rotating-angle smeared crack modeling approach and can implement either the Modified Compression Field Theory (MCFT) and Disturbed Stress Field Model (DSFM) by Vecchio (2000). VecTor2 utilizes an iterative secant stiffness algorithm to produce an efficient and robust nonlinear solution technique. The application has been validated by extensive experimental testing to corroborate its ability to predict the load-deformation response of a variety of reinforced concrete structures (Palermo & Vecchio, 2004). VecTor2 is also able to model concrete expansion and confinement, cyclic loading and hysteretic response, construction and loading chronology for repair applications, bond slip, crack shear slip deformations, reinforcement dowel action, reinforcement buckling, and crack allocation processes.

2.3 *UI-SIMCOR: multi-platform distributed analysis framework*

Different state-of-the-art analysis software packages have unique features that other competing packages do not have. The main advantage of multi-platform simulation is the use of the unique features of analytical tools in an integrated fashion. The concept of multi-platform simulation is implemented using the pseudo-dynamic (PSD) simulation approach combined with sub-structuring. In the latter simulation, a structure is subdivided into several modules that can be either physically tested or computationally simulated. UI-SIMCOR (Kwon et al., 2005) was developed for this purpose. The Operator Splitting method in conjunction with the α-modified Newmark scheme

(α-OS method, Combescure & Pegon, 1997) is implemented as a time-stepping analysis scheme. The main feature of UI-SIMCOR is that it is capable of coordinating any number of analysis tools. Interface applications are currently available for ZEUS-NL, FedeasLab (Filippou & Constantinides, 2004), VecTor2, and ABAQUS (Hibbit et al., 2001). Any number of testing sites, or a mixture of analysis tools and testing sites can be incorporated into a pseudo-dynamic multi-platform simulation. It employs software or hardware supporting NEESgrid Teleoperation Control Protocol, NTCP (Pearlman et al., 2004) as well as TCP-IP connections outside of the NEES system. It is also capable of using the same analysis platform while modeling different parts of the system on different processors, thus minimizing computational run time. In this study, UI-SIMCOR is used to combine VecTor2 and ZEUS-NL to model shear-walls and frame elements.

3 Application to reference building

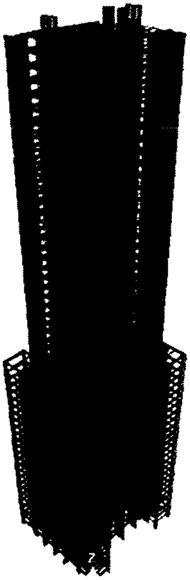
3.1 *Configuration of structure*

A newly constructed high-rise building, Tower C03 of the Jumeirah Beach development in Dubai, United Arab Emirates, was chosen as a reference structure for MDFEA. It has a complex RC dual-core wall system and RC outer frames, as shown in Figure 1, which make it an ideal candidate for MDFEA. Static pushover analyses and dynamic response history analyses were performed for Frame F4 along its strong direction. The main features of this building are as shown in Table 1.

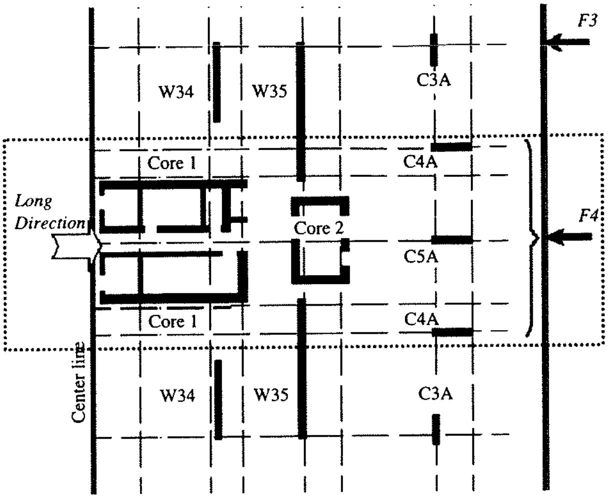
3.2 *Sub-structural modeling*

The selected 2D frame F4 of reference building, Figure 1, is divided into two main structural components, a box-shaped core wall which is Core 1 in Figure 1b and a perimeter moment resisting frame. The core walls from the 1st through 10th stories, which are likely to fail in shear, are modeled using 2D RC continuum elements in VecTor2. Such continuum elements have different thickness values reflecting wall boundary and web geometric characteristics. The core walls from the 11th story and above are approximated with fiber based section elements in ZEUS-NL. The entire structure is subdivided into three modules.

- Module 1: 1st ~ 10th story left wall modeled in VecTor2. This region is modeled in VecTor2. The first 10-stories of the wall is modeled using 2D rectangular elements whose behavior can be captured using the MCFT (Vecchio & Collins, 1986). The mesh size is around 200 mm which is within 10~20 times of aggregate size as recommended (Wong & Vecchio, 2002). Concrete constitutive models are based on Modified Popovics curve by Collins & Porasz (1989), which considers both pre-peak and post-peak concrete behavior. The confinement effects are considered according to Kupfer et al. (1969). The reversed cyclic loading curves of concrete proposed by Palermo & Vecchio (2003) is employed in the analysis.
- Module 2: 1st~10th story right wall in VecTor2. Module 2 is identical to Module 1.
- Module 3: Remaining structural components including all frame members and the core walls from the 11th to the top story.



(a) 3D building frame model in SAP2000



(b) Typical plan view

Figure 1 Reference building structure and half plane view.

Table 1 Main features of reference building.

Features	Description
Height (m)	184
Total Stories	54
Regular Storey Height (m)	3.400
Irregular Storey Height (m)	4.488
Core Walls (m)	9.43 × 3.25 (8.48 × 2.55) (1st~5th Stories)
(Exterior and Interior Size)	9.33 × 3.15 (8.48 × 2.55) (6th~20th Stories)
	9.18 × 3.05 (8.48 × 2.55) (21st~54th Stories)
Concrete f'_c (MPa)	60 (wall); 40 (slab)
Reinforcing Bars f_y (MPa)	421 (Grade 60)

As described earlier, the lower 10 stories of the wall are modeled using 2D continuum elements in VecTor2, while the walls above this level are modeled using beam-column elements in ZEUS-NL. In this approach, there are two types of interfaces: 1) frame elements interfacing with continuum elements at the side of wall, Figure 2; 2) upper-wall modeled with frame elements and lower-wall modeled with continuum elements, Figure 3. The boundary conditions of these two types of interfaces are described in the following.

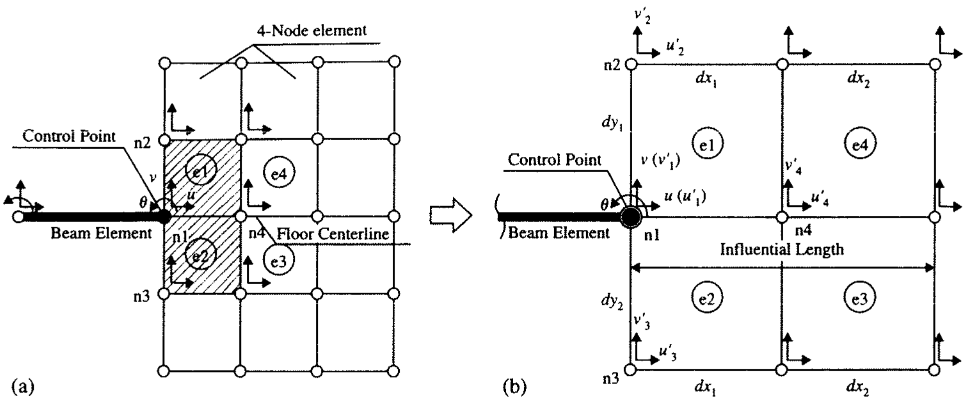


Figure 2 Frame beam element and wall continuum element interface.

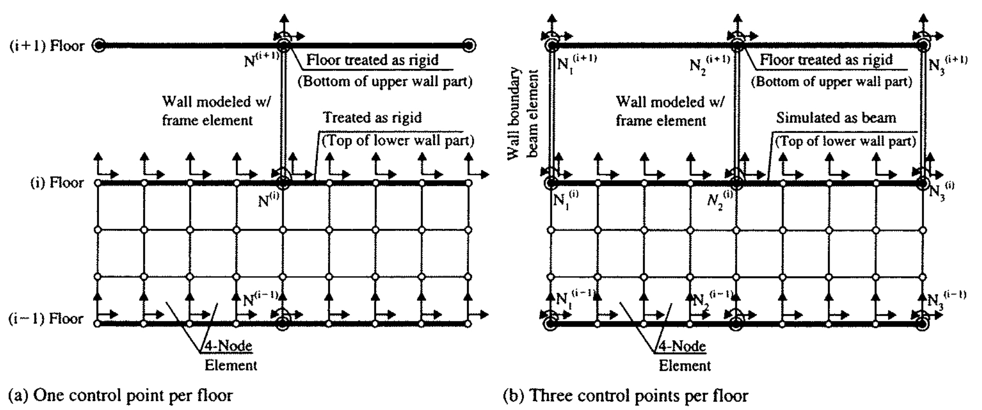


Figure 3 Upper wall beam and lower wall continuum element interface models.

3.2.1 *Interface modeling between beam and wall elements*

UI-SIMCOR (Kwon et al., 2005) uses control points in the sub-structure models. The control points are nodes with lumped masses or nodes which are shared by two or more substructures. These control points need to be defined in order to form the global mass and stiffness matrices necessary in pseudo-dynamic (PSD) algorithm employed in UI-SIMCOR, and to serve as the common interfaces between sub-structures.

There are two ways to simulate the interface between frame elements modeled with Zeus-NL and between continuum elements modeled with Vector2. One method is to use membrane elements for the wall with drilling (out-of-plane rotational) DOFs, but this is not available in VecTor2. The second method and the one used in this study is to simulate displacement and rotational compatibility between nodes of frame elements having three DOFs per node and nodes of 4-noded plane-stress element having two

DOFs per node. To illustrate this approach, consider node n1 in Figure 2 that are common to the beam element and plane-stress elements e1 and e2. In order to satisfy compatibility, constraint equations are added between the nodes of the two models to satisfy compatibility of rotation at these common (control) points.

In UI-SIMCOR, displacements are always imposed at control points and reaction forces are obtained as feedback at the same DOFs. Thus, combining the models requires the calculation of equivalent nodal displacement of continuum elements at the interface connected to control point. The constraint equations for beam-continuum coupling are derived for the interface region shown in Figure 2b, which is formed by elements e1 and e2, and nodes n1 to n4. It is assumed that the left edges of elements e1 and e2 remain straight during deformation.

Hence, the rigid body motion geometric relationships are applied to calculate nodal displacements at left edges as described by Equation (1).

$$\begin{Bmatrix} u_1' \\ v_1' \end{Bmatrix} = \begin{Bmatrix} u \\ v \end{Bmatrix}; \ \begin{Bmatrix} u_2' \\ v_2' \end{Bmatrix} = \begin{Bmatrix} u - dy_1 \sin\theta \\ v - dy_1(1-\cos\theta) \end{Bmatrix}; \ \begin{Bmatrix} u_3' \\ v_3' \end{Bmatrix} = \begin{Bmatrix} u + dy_2 \sin\theta \\ v + dy_2\,(1-\cos\theta) \end{Bmatrix} \tag{1}$$

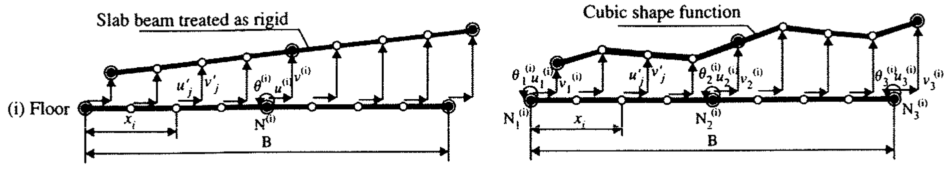
where, $[u, v, \theta]$ are the displacements at control point. For the nodes along the beam centerline, not all nodes will be considered as being on an interface. Only those within the influential length (on account of usual anchorage requirements for rebar) are considered and here the middle node n4 in Figure 2 is such a node. For the middle node n4, it is assumed that the horizontal and vertical movements are generated by the control point displacement based on beam shape functions following Equation (2).

$$\begin{Bmatrix} u_4' \\ v_4' \end{Bmatrix} = \begin{bmatrix} (1-\xi) & 0 & 0 & \xi & 0 & 0 \\ 0 & (1-3\xi^2+2\xi^3) & (\xi-2\xi^2+\xi^3)l_e & 0 & (3\xi^2-2\xi^3) & (\xi^3-\xi^2)l_e \end{bmatrix} \begin{Bmatrix} u \\ v \\ \theta \\ 0 \\ 0 \\ 0 \end{Bmatrix} \tag{2}$$

where $\xi = x/l_e$, here the element length $l_e = dx_1 + dx_2$. The feedback control point reactions are computed from the nodal forces at these four nodes through equilibrium conditions described by Equation (3).

$$F_x = \sum_{i=1}^{4} f_{xi}; \ F_y = \sum_{i=1}^{4} f_{yi}; \ M_z = \sum_{i=1}^{4} (f_{xi}y_i + f_{yi}x_i) \tag{3}$$

The VecTor2 post-processor can compute and output reaction forces corresponding to the nodes imposed with displacement. MATLAB codes were written as UI-SIMCOR plug-ins to implement functionalities such as receiving commands from UI-SIMCOR



(a) One-control-point approach (b) Three-control-point approach

Figure 4 Wall interface interpolation approaches and DOFs.

through network, calculating interface nodal displacements for VecTor2 model, running VecTor2, and extracting reaction forces.

3.2.2 *Interface modeling between upper wall beam and wall elements*

Wall on 11th story and above can be represented in two ways. The first method is modeling the wall on each floor as a single frame element with large section, Figure 3(a). In this approach, a rigid beam can be placed at the interface of upper wall modeled with frame elements and lower wall with continuum elements to transfer rotational DOF at the interface. The other approach is to model upper wall with multiple elements, Figure 3(b). For instance, the upper-wall frame element can be divided into three components including two boundary regions and a middle web area, all modeled using fiber section elements in ZEUS-NL. The floor slab may strengthen the adjacent region of the wall and at the same time affect wall deformations. Due to the flexibility of the slab-beam and the large attached mass, very significant external loads can be induced in the dynamic analyses. To avoid over-restraining the continuum elements, the floor is considered to have some flexibility as opposed to the full rigidity used in the first method.

The rigid or very stiff beam elements at the interface of upper and lower walls can be represented by constraint equation which constrains relative displacements of DOFs. The shapes of constraint equations for each approach are illustrated in Figure 4. Mathematical expression of the constraint equation is as follows.

One-control-point approach: In this approach, the rigid body motion assumption is made for the floor slab system as shown in Figure 4(a). The rotational DOF at this control point will generate a linear variation in vertical displacement at all nodes along the ith floor. The constraint equations for both upper wall to lower wall and inter-storey lower wall interfaces are derived using Equation (4). The control point reaction forces are computed from the stress resultants at all of the nodes through equilibrium conditions as evaluated by Equation (5).

$$\begin{Bmatrix} u'_j \\ v'_j \end{Bmatrix} = \begin{Bmatrix} u_i + \left(\dfrac{B}{2} - x_j\right)(1 - \cos\theta_i) \\ v_i - \left(\dfrac{B}{2} - x_j\right)\sin\theta_i \end{Bmatrix} \qquad (4)$$

$$\begin{Bmatrix} F_{xi} \\ F_{yi} \\ M_{zi} \end{Bmatrix} = \begin{Bmatrix} \sum_{j=1}^{Ni} f_{xj} \\ \sum_{j=1}^{Ni} f_{yj} \\ \sum_{j=1}^{Ni} f_{yj}\left(\frac{B}{2} - x_j\right) \end{Bmatrix} \tag{5}$$

where, i – Control point number, $i = 1, 2, \ldots, N_i$, and N_i is the total number of nodes along ith floor in VecTor2 model.

Three-control-point approach: As discussed previously, instead of employing a rigid body motion assumption, beam shape functions are used for the calculation of the equivalent nodal displacements in the VecTor2 model. In the above approach, the interface floor system is divided into two beams connected by three control points. In Figure 4(b), control points N_1, N_2, and N_3 form two beam members with lengths equal to half of the wall width. Cubic shape functions are used for the interpolation of continuum model nodal displacement loads $[u'_j, v'_j]$ from $[u, v, \theta]^i_{1\sim3}$ at these three control points as follows. The shape functions for the two beam members are defined as follows:

$$[N] = \begin{bmatrix} (1-\xi) & 0 & 0 & \xi & 0 & 0 \\ 0 & (1-3\xi^2+2\xi^3) & (\xi-2\xi^2+\xi^3)l_e & 0 & (3\xi^2-2\xi^3) & (\xi^3-\xi^2)l_e \end{bmatrix} \tag{6}$$

$$\text{where, } \xi = \begin{cases} \dfrac{x}{l_e}, & \text{if } x \le \dfrac{B}{2} \\ \dfrac{(x-B/2)}{l_e}, & \text{if } x > \dfrac{B}{2} \end{cases}, \text{ the element length } l_e = \frac{B}{2}$$

The nodal displacements at all the nodes along ith floor can then be computed as:

$$\begin{Bmatrix} u'_j \\ v'_j \end{Bmatrix} = \begin{cases} [N]\,[u^i_1\ v^i_1\ \theta^i_1\ u^i_2\ v^i_2\ \theta^i_2]^T, & \text{for } 0 \le x_j \le \dfrac{B}{2} \\ [N]\,[u^i_2\ v^i_2\ \theta^i_2\ u^i_3\ v^i_3\ \theta^i_3]^T, & \text{for } \dfrac{B}{2} \le x_j \le B \end{cases} \tag{7}$$

where, $j = 1, 2, \ldots, N_i$, N_i are the total number of nodes along ith floor in VecTor2 model, and B represents the wall width. The feedback control point reactions are computed from nodal force results from the VecTor2 output using an equivalent nodal force concept for beam elements as expressed in Equations (8)~(10).

$$[F_{x1}\,F_{y1}\,M_{z1}\,F^1_{x2}\,F^1_{y2}\,M^1_{z2}]^i = \left[\sum_{j=1}^{m1}\left([N]^T\begin{Bmatrix} f_{xj} \\ f_{yj}\end{Bmatrix}\right)\right]^T, \quad \text{for } 0 \le x_j \le \frac{B}{2} \tag{8}$$

$$[F^2_{x2}\,F^2_{y2}\,M^2_{z2}\,F_{x3}\,F_{y3}\,M_{z3}]^i = \left[\sum_{j=m1}^{m2}\left([N]^T\begin{Bmatrix} f_{xj} \\ f_{yj}\end{Bmatrix}\right)\right]^T, \quad \text{for } \frac{B}{2} \le x_j \le B \tag{9}$$

$$[F_{x2}\,F_{y2}\,M_{z2}]^i = [F^1_{x2}\,F^1_{y2}\,M^1_{z2}]^i + [F^2_{x2}\,F^2_{y2}\,M^2_{z2}]^i \tag{10}$$

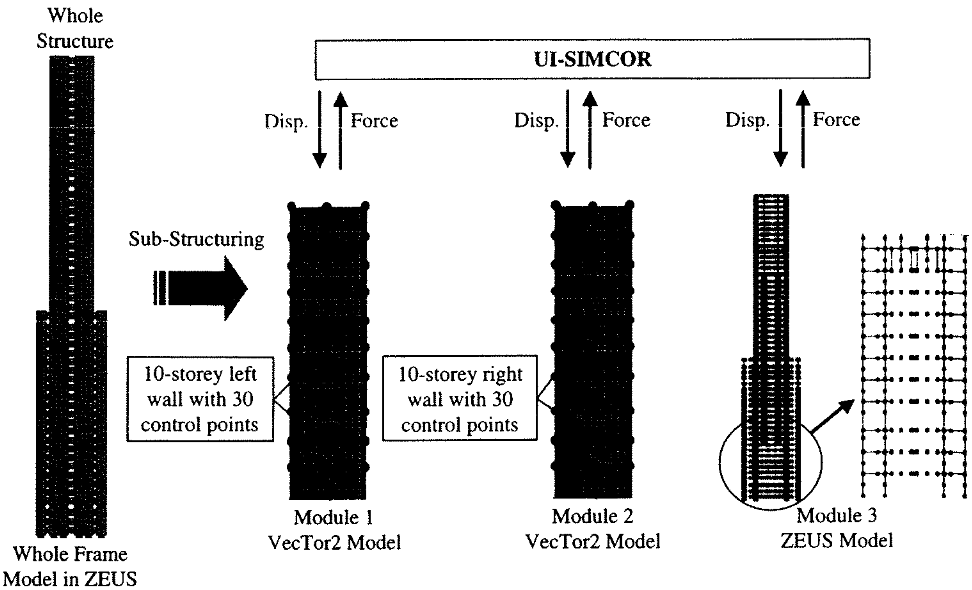


Figure 5 Multi-resolution distributed simulation for reference building combining ZEUS-NL and VecTor2 within UI-SIMCOR.

where, $m1$, $m2$ are the number of nodes at middle and right end of the floor, $[f_{xj}, f_{yj}]$ are the forces at jth node in VecTor2.

Both of these approaches have been investigated and compared on the basis of accuracy, runtime and stability. The three-control-point approach proved to be more realistic by introducing flexibility of the floor as was expected in the real structure. The rigid slab assumptions put severe restraints on the floor nodes and thereby overestimated the stiffness of the lower 10-stories of the walls, which led to smaller flexural deformations of the wall and underestimated the effects on lateral drift. The use of the rigid body motion assumption restricted the development of cracking. The runtime required by one control point approach was somewhat shorter than that with the use of three control points. Based on this evaluation, the accuracy of the results was considered to be more important than runtime and therefore the three-control-point approach was employed for the MDFEA conducted in this study.

3.2.3 *Integrated MDFEA structural modeling*

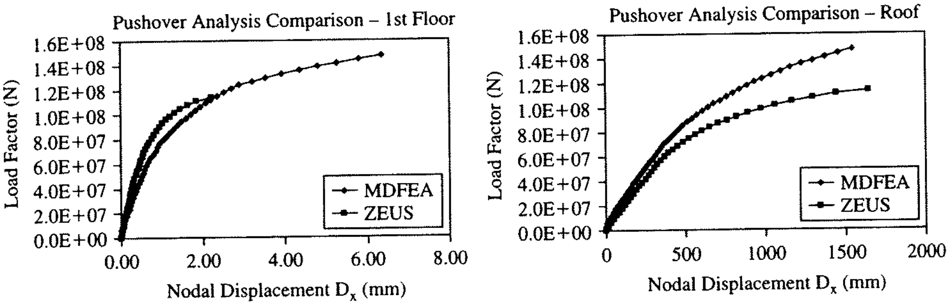
The MDFEA framework and sub-structuring methodology used for the 54-story case study building is shown in Figure 5. Dynamic response history as well as static pushover analyses are conducted using the distributed simulation approach. The characteristics of the model and control DOFs are described in Table 2.

3.3 *Static pushover analysis*

Static pushover analyses are conducted for the reference building in order to estimate its ultimate strength and ductility capacity. Gravity loads are applied to the building

Table 2 MDFEA model size and control DOFs.

Module No.	*Node Number*	*Element Number*	*Control Node*	*Effective DOF*
1 – Left Wall VecTor2 Model	3640	3502	30	90
2 – Right Wall VecTor2 Model	3640	3502	30	90
3 – Whole Frame ZEUS Model	1160	1672	306	426



(a) Response at 1st storey (b) Response at roof

Figure 6 Pushover comparisons between results from MDFEA and complete ZEUS-NL.

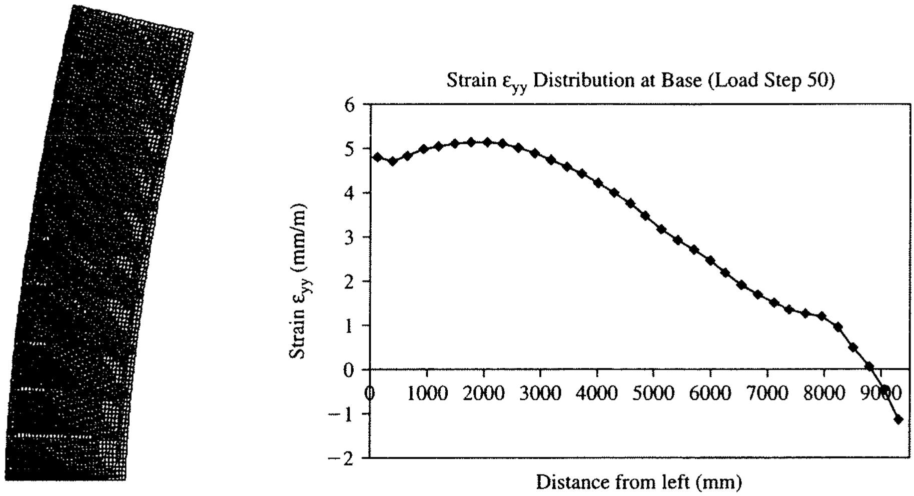
prior to conducting the static pushover analysis. Two analyses are conducted, one using the MDFEA framework and the other in which the structure is entirely modeled with frame elements in ZEUS-NL. A comparison of the results from these analyses is presented in Figure 6.

This comparison illustrates that the lateral drift in the lower part of the wall has more flexibility and ductility in MDFEA than in the ZEUS-NL analysis. This is mainly due to the much larger shear deformation contributions that are captured in the continuum model of the MDFEA. At higher load levels, the ZEUS-NL model exhibits lower stiffness and ultimately less strength than the MDFEA model. This is mainly because, the plane section assumption in the fiber approach leads to concrete crushing at wall's base earlier than the concrete compressive capacity is reached in the continuum model.

In the MDFEA approach, load redistribution is repeatedly performed at each load step and a confined concrete strength model is applied in the regions of highest compressive stress that follows the Kupfer-Richart Model, Wong & Vecchio (2002), as expressed in Equation (11). This latter feature leads to increased wall capacity and ductility under high load levels even after extensive cracking has been calculated to occur.

$$\beta_l = \left[1 + 0.92\left(\frac{f_{cn}}{f'_c}\right) - 0.76\left(\frac{f_{cn}}{f'_c}\right)^2\right] + 4.1\left(\frac{f_{cl}}{f'_c}\right) \tag{11}$$

where, $f_{cn} = -(f_{c2} - f_{c1}) > 0$, $f_{cl} = -f_{c1} > 0$, $f_{c2} < f_{c1} < 0$



(a) Cracked deformed shape (step 50, scale factor: 20)

(b) Strain ε_{yy} distribution at wall base section

Figure 7 Results from MDFEA pushover analysis

Table 3 Selected ground motion records for MDFEA.

Earthquake	*Record*	*M*	*Station Data Source*	*Distance (km)*	*Site Soil Condition*	*PGA (g)*
Chi-Chi, Taiwan 1999/09/20	Chi-Chi_close_stiff	7.6	CHY028-N, (CWB)	7.31	Stiff	0.821
Kocaeli, Turkey 1999/08/17	Kocaeli_close_stiff	7.4	SKR090, Sakarya (ERD)	3.1	Stiff	0.376
Kobe, Japan, 1/16/1995	Kobe_close_stiff	6.9	TAZ090 Takarazuka, (CUE)	1.2	Stiff	0.694
Kobe, Japan, 1/16/1995	Kobe_close_soft	6.9	SHI000, Shin-Osaka, (CUE)	15.5	Soft	0.243
Loma Prieta, USA 1989/10/18	Loma_dist_soft	6.9	SFO090 58223, (CDMG)	64.4	Soft	0.329

Figure 7 shows the extent of cracking, the deformed wall shape and vertical strain distribution along the base section at load step 50. It is observed from Figure 7a that the wall deforms and is damaged in flexural-shear mode under the incremental pushover loads. The curved vertical strain distribution over the horizontal cross section also illustrated that plane section assumptions are not really happening inside the wall.

3.4 *Dynamic response history analysis*

Inelastic dynamic response history analyses are conducted using the MDFEA framework for the reference building using selected representative ground motion records. Ground motions were selected to encompass different magnitudes, distance to source, and site soil conditions. The variation of input ground motion shown in Table 3 is

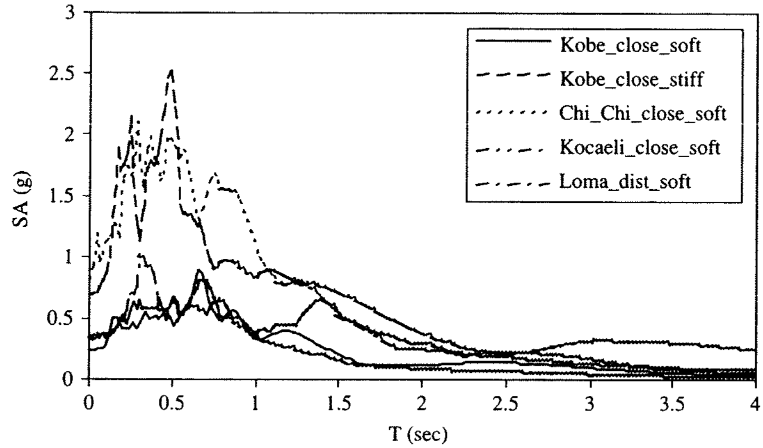


Figure 8 Response spectrum of selected GMs for MDFEA.

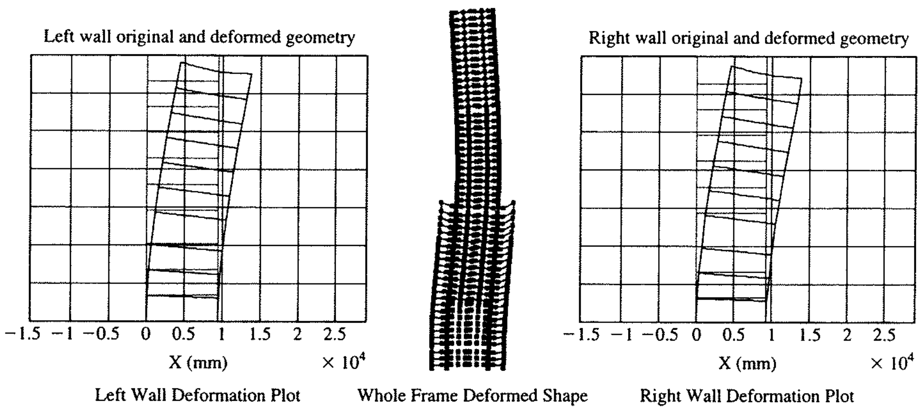
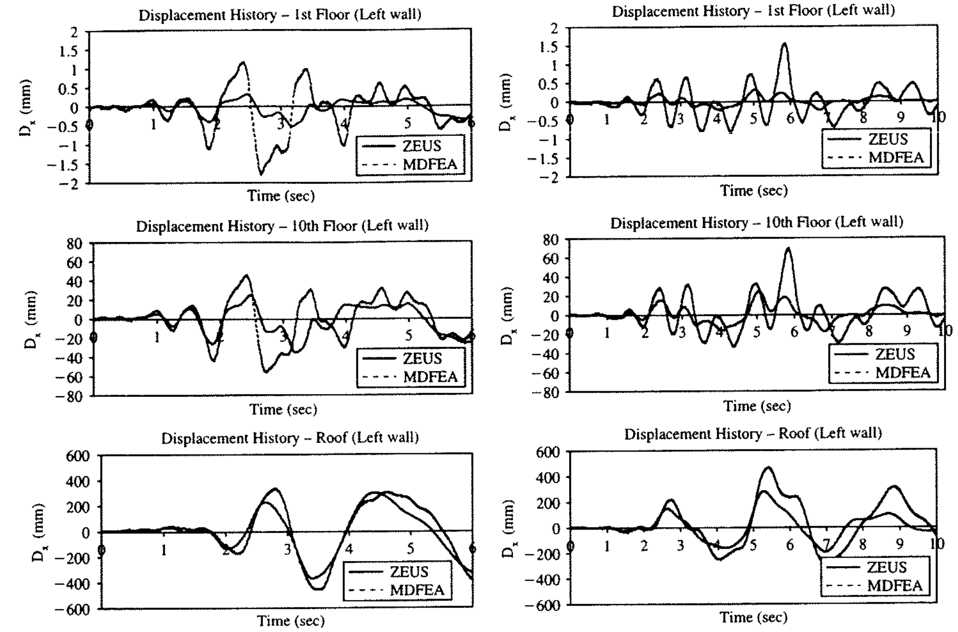


Figure 9 Deformed shapes of three modules from THA using the MDFEA framework.

intended to evaluate the robustness of the MDFEA algorithm for complex structural systems under different types of seismic excitations. The elastic spectrum acceleration diagrams (damping ratio 5%) of the selected GMs are shown in Figure 8.

Figure 9 presents the deformed sub-structure shapes for the reference building during a response time history analysis (THA). The shapes illustrate the synchronized seismic responses of two core walls and the frame as well as the flexibility of the floor and shear deformations in the wall.

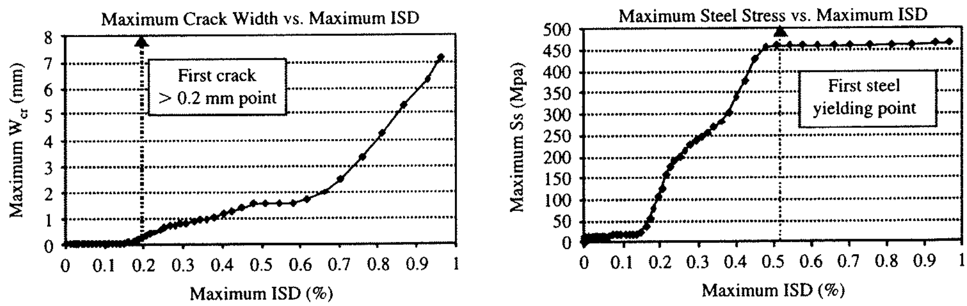
In Figure 10, two sets of response history analysis results using both MDFEA framework and the pure frame model using ZEUS-NL are presented. The left wall displacement responses at different height levels are compared between these two models, including total drifts at 1st storey, 10th storey (top of the wall VecTor2 models in modules 1 and 2) and the roof.



(a) GM record Kobe_close_stiff

(b) GM record Kobe_close_soft

Figure 10 Sample displacement histories and comparisons between MDFEA and ZEUS Models.



(a) Limit state 1 – Serviceability by considerable cracking (W_{cr} > 0.2 mm)

(b) Limit state 2 – Damage control by wall rebar yielding (fy >= 460 MPa)

Figure 11 Quantitative definitions for limit states 1 and 2 using MDFEA results.

The results presented in Figure 11 illustrate that the drift computed from MDFEA at the lower levels is much larger than that from ZEUS-NL pure frame model, while the roof drifts from the two models are relatively close.

The comparisons presented above indicate that pure-frame analyses may not be able to sufficiently predict some important shear deformation features of the response of the 54-story high-rise building.

3.5 *Significance of the MDFEA framework*

With the use of the MDFEA framework proposed herein, it becomes feasible to accurately and efficiently predict the static and dynamic response of complex structures. This framework will help researchers tackle important problems, such as developing performance limit states definitions for seismic risk analysis. The framework is also ideally suited to fragility assessment studies. For RC structures, all the information available from MDFEA, including concrete stress and strain distributions, steel stresses and crack patterns throughout the structural walls, are available for assessing a structures performance. For example, it is now possible to define new limit states for serviceability that consider the state of cracking in the core wall or new limit states for damage control that more accurately consider the yielding of the longitudinal reinforcement. Based on previous pushover analyses, maximum concrete crack width and steel stress can be correlated to global deformation measures including inter-storey drift ratio (ISD) during the loading history, as shown in Figure 11.

3.6 *Computational errors and stability*

With the use of this MDFEA framework, nonlinearities are accounted for in the individual computational modules, such as in ZEUS-NL and VecTor2. The different features of these modules, including finite element model resolutions, theoretical algorithms and numerical techniques, will lead to different accuracy levels and different deviations of strain and stress resultants. Hence, the actual movements and reaction feedbacks at control points will contain errors combined from multiple modules that are difficult to eliminate. Another error source originates from the interface modeling, such as in this case study example in which either rigid or flexible slab assumptions were used.

These errors can be transferred to the next step while the new displacement commands are sent to all modules by UI-SIMCOR based on the calculations from the previous step. Thus, the errors are accumulated along the load history and may lead to numerical divergence. In this study, error monitoring was applied for each step by comparing the imposed displacements and actual movements. This enables an evaluation of the stability of the model and the reliability of the results.

Another computational instability may be caused by numerical divergence within any of the analytical tools being combined. ZEUS-NL will stop the analysis automatically if convergence is not achieved after the predefined multi-level step size reduction technique is used. While for VecTor2, the analysis will be terminated if the convergence limit cannot be satisfied for two consecutive steps. These instabilities are more straightforward to assess since the consecutive divergences are not due to random numerical errors but indicate the occurrence of either global or local structural failures.

4 Conclusions

There is a dearth of accurate, efficient and reliable analytical approaches for the inelastic static and dynamic analyses of complex reinforced concrete and composite high-rise buildings under extreme loads taking into account shear-flexure-axial interaction, crack propagation and other detailed features of concrete response. In this study, a new approach termed multi-resolution distributed finite element analysis (MDFEA) is proposed and used to analyze a reference RC high-rise building with a dual core wall-frame system. Below, a summary of the features of the study and highlights of its conclusions are given:

- Two advanced analytical platforms ZEUS-NL and VecTor2 were used to effectively model the frame and wall separately, based on the unique algorithms and functionalities of the two programs.
- A 'simulation coordinator' – UI-SIMCOR (Kwon et al., 2005), was used to combine the best features of different FEA software for modeling different components within one system. Through sub-structuring, global integration and network data flow, a distributed FEA simulation was completed.
- A real 54-story high-rise building with a dual core wall-frame structural system was selected as the case study example. By using the MDFEA framework, both static pushover and dynamic response history analyses were conducted. Multiple modules corresponding to frame and wall components were built in UI-SIMCOR and analyzed with frame-wall interaction effects fully considered in a step-by-step manner.
- The comparisons from both pushover and response history analysis highlight that due to the influence of shear, the use of the multi-resolution approach is illustrated to be able to capture critical aspects of the behavior more sufficiently than some traditional methodologies performing pure frame analysis. The use of a MDFEA approach can account for response limit states including shear-flexure-axial interaction.

With the completed and verified functionality of the proposed MDFEA framework, it is practical to extend the application to other high-rise buildings and to other complex structures. This framework is not restricted to combining ZEUS-NL and VecTor2, but rather can be used to integrate the necessary features of any number of FE packages.

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