A SOFTWARE FRAMEWORK FOR SUPPORTING CLUSTER-TO-CLUSTER COMPUTING ON LARGE-SCALE STRUCTURAL ANALYSIS PROBLEMS

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ABSTRACT

For the realistic simulation of structural engineering systems, the numerical model of a structural system must be complex enough to capture the detailed behaviors of the real system at various scales. The computation of such a large-scale simulation problem requires massive computing resources integrated together by advanced high performance computing technique. The Internet has revolutionized the way computing is done. Internet-based distributed computing is perceived as the most promising avenue to achieve further computing power. Virtually an infinite number of machines can be connected in this way, theoretically leading to unlimited computational capabilities. However, Internet communication is expected to be a significant bottleneck. To incorporate the Internet into distributed computations, the traditional parallel structural analysis procedure must be revised from the architectural level to minimize the amount of data being communicated and the frequency of data communication over the Internet.

A new grid-based simulation methodology for the realistic simulation of structural engineering systems is proposed and investigated in this paper. Two levels of parallel processing will be involved in this framework: multiple local distributed computing environments connected by Internet to form a grid-based cluster-to-cluster distributed computing environment. To successfully realize realistic simulation in this computing environment, a large-scale structural simulation task is decomposed into the simulations of a simplified global model and several detailed component models using various scales. These correlated multi-scale simulation tasks are distributed amongst clusters and connected together in a multi-level hierarchy and then coordinated over the Internet to complete the realistic simulation. This paper also presents a software framework for supporting the proposed multi-scale simulation approach in a grid-based cluster-to-cluster distributed computing environment. The program architecture design allows the integration of several multi-scale models as clients and servers under a single platform. Such integration will permit the realization of more realistic simulations of structural systems.

KEY WORDS

structural analysis, realistic simulation, distributed computing, grid computing, Internet.

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INTRODUCTION

Advances in computer technology and numerical methods have allowed the simulation of engineering problems that traditionally have been addressed via experimentation and theoretical models. Some industries have been able to design sophisticated engineered systems based solely on computer simulation. In addition, many complex phenomena, such as airplane crashes and car accidents, can already be analyzed by computer simulations. In the context of structural engineering, using computer simulation to realistically represent the behavior of structural systems in detail in various situations, such as the global response and the detailed damage to a structure during a major earthquake, is also a goal which must be achieved by engineers.

In comparison with other engineering systems, structural engineering systems such as bridges and buildings usually are large-scale and contain the effects of various structural components and materials at various scales. Therefore, to successfully realize the realistic simulation of structural systems, the structural model must be able to capture the behaviors of the global system and all the detailed local mechanisms. Modeling the whole structural system in every detail using very fine meshes as the way to simulate the response of structural components is an approach to achieve this. However, the resulting models would be enormous and hard to handle efficiently using current computational power.

High-performance computing is the key to the investigation of problems that are computationally intensive, such as the realistic simulation of structural engineering systems. At the dawn of parallel computing, shared memory machines dominated. In this kind of hardware architecture, communication between processes was irrelevant. Thus, few modifications of the finite element analysis algorithms were necessitated by the computational hardware. As distributed memory computers and clusters of networked workstations were introduced, communication times between processes became significant. This brought about innovations in the finite element analysis using domain decomposition algorithms by dividing tasks into a few loosely coupled subtasks to minimize the communication penalty. The well-known domain decomposition methods include substructuring (static condensation, dynamic reduction), parallel central difference algorithm by Hajjar and Abel (1989), the Iterative Group Implicit (IGI) algorithm by Modak and Sotelino (2000), Finite Element Tearing and Interconnecting (FETI) by Farhat and Roux (1991), and the nonlinear substructuring algorithm by Chen and Archer (2005).

Presently, grid computing is being perceived as the most promising avenue to achieve further computational power. Virtually an infinite number of machines can be connected via the Internet, theoretically leading to unlimited computational capabilities. However, unless each subtask is highly independent, Internet communication can render impossible any possible gain in efficiency from a grid-based distributed application. Depending on the time of the day, the traffic in the Internet can be such that no timely communication is possible. In addition, in all of the above domain decomposition methods, there is a limitation to the number of processors which produce efficiency. Therefore, extending those methods directly for running on a platform which consists of massive machines connected by comparatively slow, over-utilized communication channels to efficiently perform a simulation is not a trivial task. New methodologies are necessary that minimize the amount of data being communicated and the frequency of data communication.

Since decomposing a complex model and distributing the decomposed tasks to all available machines will not work in a grid-based computing environment due to the Internet-imposed communication time obstacle, a new grid-based simulation methodology for the realistic simulation of structural engineering systems is proposed and investigated in this paper. Two levels of parallel processing will be involved in this framework: multiple local distributed computing environments connected by the Internet to form a grid-based cluster-to-cluster distributed computing environment. To successfully realize realistic simulation in this computing environment, a large-scale structural simulation task is decomposed into the simulations of a simplified global model and several detailed component models at various scales. These correlated multi-scale simulation tasks are distributed amongst clusters connected together via Internet to form a multi-level modeling hierarchy, and then these simulations, in separated clusters, coordinate with each other over the Internet to complete the realistic simulation of a whole structural system. This paper also presents a software framework for supporting the proposed realistic simulation approach in a grid-based cluster-to-cluster distributed computing environment. The program architecture design allows the integration of several multi-scale models as clients and servers under a single platform. Such integration will permit the realization of more realistic simulations on structural systems.

CLUSTER-TO-CLUSTER DISTRIBUTED COMPUTING ENVIRONMENT

A simple one-level grid computing environment can be described as a massive collection of heterogeneous machines connected by comparatively slow, over-utilized communication channels. Applications for running in this kind of environment must assume any communication is over the Internet, no matter whether the machine to be communicated with is local or remote in fact. Thus, this kind of framework is only suitable for distributed computing problems for which each subtask is independent or highly independent, so that time for Internet communication among massive machines is not necessary or is insignificant. For existing distributed finite element analysis algorithms, communication time is significant and there is a limitation to the number of processors which can achieve efficiency. Therefore, there is no way to extend existing algorithms to be applicable in a simple one-level grid computing environment.

For reducing the Internet communication bottleneck by organizing the hardware configuration of a grid-based environment, a cluster-to-cluster distributed computing framework, as shown conceptually in Figure 1, is proposed. This framework involves two levels of parallel processing: multiple local distributed computing environments connected by Internet to form a grid-based cluster-to-cluster distributed computing environment. In fact, each of the clusters in the framework can be a distributed memory supercomputer, a shared memory supercomputer, or just a personal computer. Most communications are between computing nodes within a cluster like a traditional cluster computing environment. Only the messages required to be exchanged between clusters are communicated between the interface computers over the Internet.

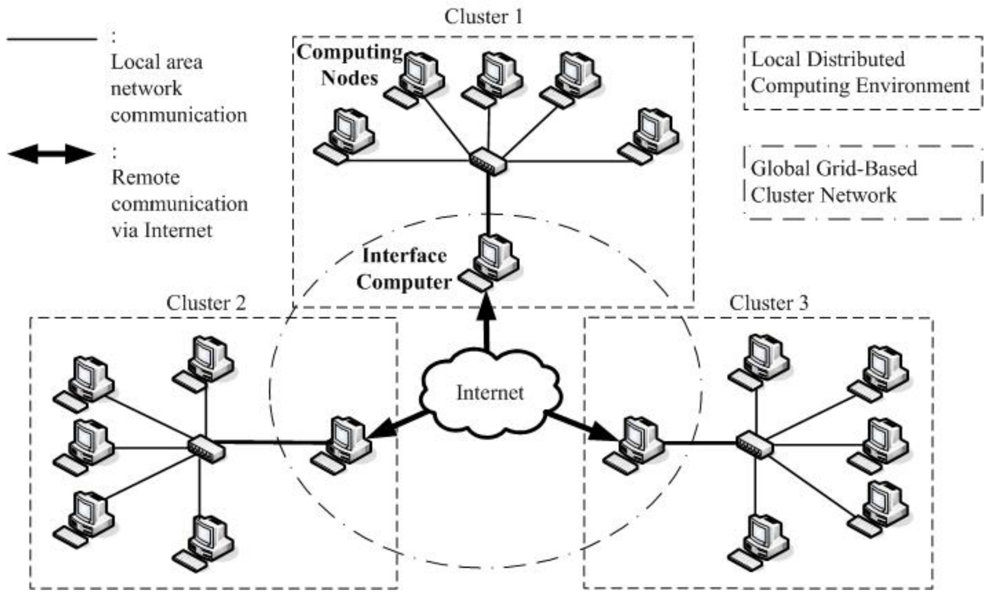

Figure 1: Cluster-to-cluster distributed computing environment

Due to the introduction of two-level parallelism, the modeling approach and computational procedure for structural simulations must be revised from the architectural level, to be applicable in the proposed cluster-to-cluster distributed computing environment. The new simulation method must minimize the amount of data being communicated and the frequency of data communication over the Internet, and keep most of the required communications within the same local area network.

MULTI-LEVEL HIERARCHICAL MODELING AND SIMULATION

In simulation of structural engineering systems, finite element analyses are often carried out to simulate the behavior of the system as a whole. In this type of analysis, simplistic models are often used for structural components, such as connections and beamcolumns. Although the global responses of structural systems can be simulated in this way, the detailed responses of their components cannot be obtained using simplistic models. On the other hand, much research has been conducted in the analysis of structural components. In this type of analysis, the structural components are modeled in very fine mesh to get detailed responses. However, these models are in isolation with no consideration of the relationship between their behavior and that of the rest of the system. Therefore, there is a need for the integration of these two levels of knowledge under a single platform. Such integration will permit the realization of more realistic simulation of structural engineering systems.

Modeling the whole structural system in every detail using very fine meshes as the way to simulate the responses of structural components is an approach to achieve this. However, the resulting models would be enormous and hard to handle efficiently using current computational power and analysis techniques. Another possible approach is proposed by using independent models of various scales for simulating the global system of a structure and its detailed components in the ways traditional structural analyses are conducted, and then trying to integrate and correlate the simulations of these multi-scale models to achieve realistic simulation of the whole structure. In this way, a detailed simulation of the whole system can be decomposed into several detailed simulations of its individual components.

To achieve this, a structural component must be modeled twice at two different scales. A simplified component model (SCM) to reside in a macro/global system to obtain the actions applied by the rest of the system, and a rigorous component model (RCM) to be analyzed in isolation to obtain its detailed responses and behavior. The two separated models, in fact, represent the same structural component in the real system, thus synchronization is required during the simulation process through communication and coordination. In addition, a rigorous model of a component can contain the simplified models of other components to result in a multi-level hierarchical modeling architecture, which is shown conceptually in Figure 2.

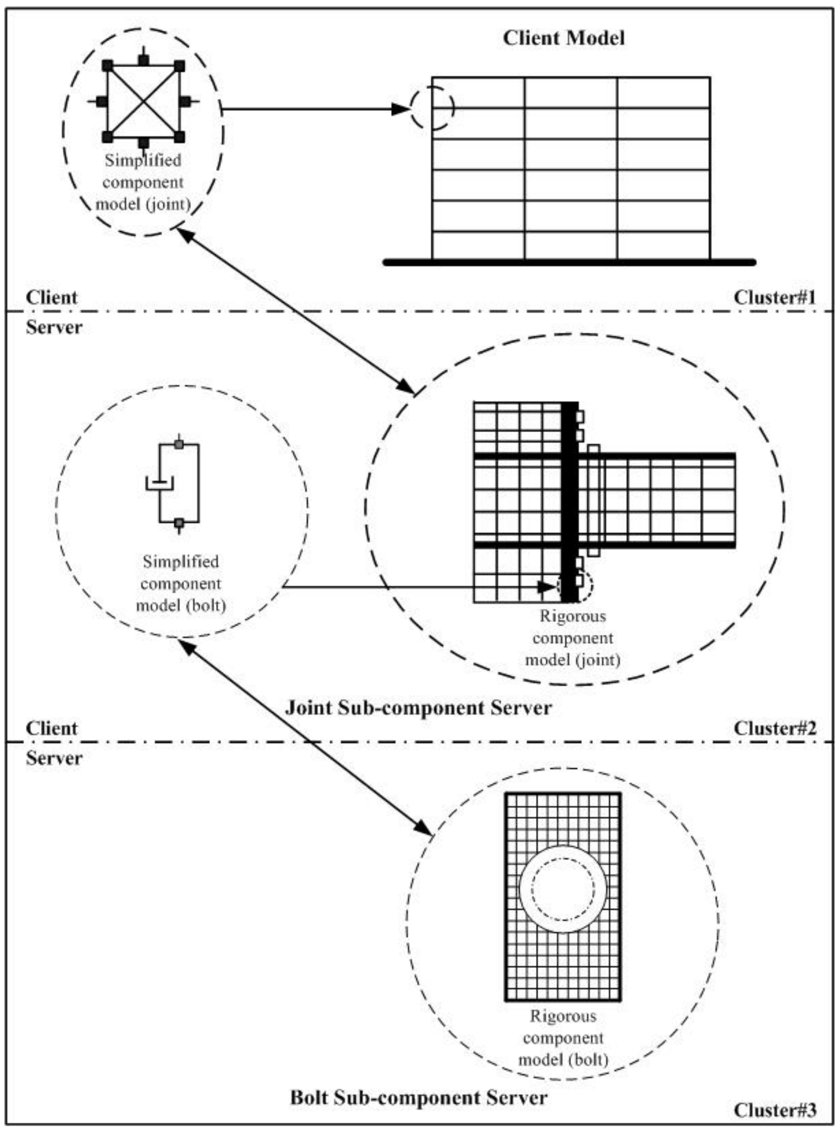

Figure 2: Multi-level hierarchical modeling and simulation

Tremendous computational power is needed to perform such a simulation. The proposed multi-level hierarchical modeling and simulation method can perfectly fit in and run in the proposed cluster-to-cluster distributed computing environment by distributing the global system model and all the rigorous component models in a hierarchy amongst clusters and interacting over the Internet. Only the information required for synchronizing corresponding simplified component models and rigorous component models must be communicated over the Internet. Thus, the communication time obstacle is removed at the architectural level by the proposed method with the proposed computing environment. The introduction of a simplified component model allows the state-update and state-query tasks of global analysis to be performed locally within the same (client) cluster. When the state of a structural component is desired by the analysis, its local simplified component model is used. Likewise, to update the state of a structural component, its local simplified component model is updated. In essence, a simplified component model acts locally as agent to the global analysis in the client cluster on behalf of the server-based rigorous component model. Any pair of corresponding models (simplified and rigorous) only needs to sporadically exchange a small amount of information over the Internet for synchronization. In this way, the Internet communication overhead can be avoided.

To successfully realize realistic simulation of structural systems by the proposed multi-level hierarchical modeling approach, there are two requirements to be achieved. First, the analysis algorithm must be able to handle the transition between distinct scales by translating a component's global behavior obtained from its macro-level model to actions on its micro-level model and a component's localized effects obtained from its micro-level model to the behavior of its macro-level model in the global system. Thus, mechanisms are required for extracting the values of displacements and stresses in a simplified component model, and then appropriately translating these quantities to the known values in the analysis of the corresponding rigorous component model, and vice versa. Second, a simplified component model must accurately describe the global behavior of the component. Otherwise, the resulting global actions on it would be invalid. Many researchers have developed simplified models that can generally achieve the goal for various structural components, such as the beamcolumn element by D'Ambrisi and Fillippou (1999). However, in some occasions, the original simplified component model may become invalid to represent the behavior of its corresponding rigorous component model. For this reason, a rigorous model must check the state of its corresponding simplified model periodically, and calibrate or update it when necessary.

SYSTEM DESIGN AND IMPLEMENTATION

The software framework to perform the proposed multi-level hierarchical modeling and simulation on the proposed cluster-to-cluster distributed computing environment consists of two modules. They are a core analysis module and a graphical user interface module. Both modules are implemented using Java, a platform-independent, net infrastructure language, so that the system can run on any (interface) computer connected to the Internet.

CORE ANALYSIS MODULE

The core analysis module is a client-server-based distributed system for handling all the information translation, Internet communication, and synchronization coordination between a simplified component on the client and a rigorous component on the server. This client-server-based system includes a C++ and MPI-based parallel object-oriented finite-element analysis program, named OOPSE (Chen and Archer (2001)), on both sides for simulations, which runs locally on a cluster of machines. The object model of the core analysis module is shown in Figure 3.

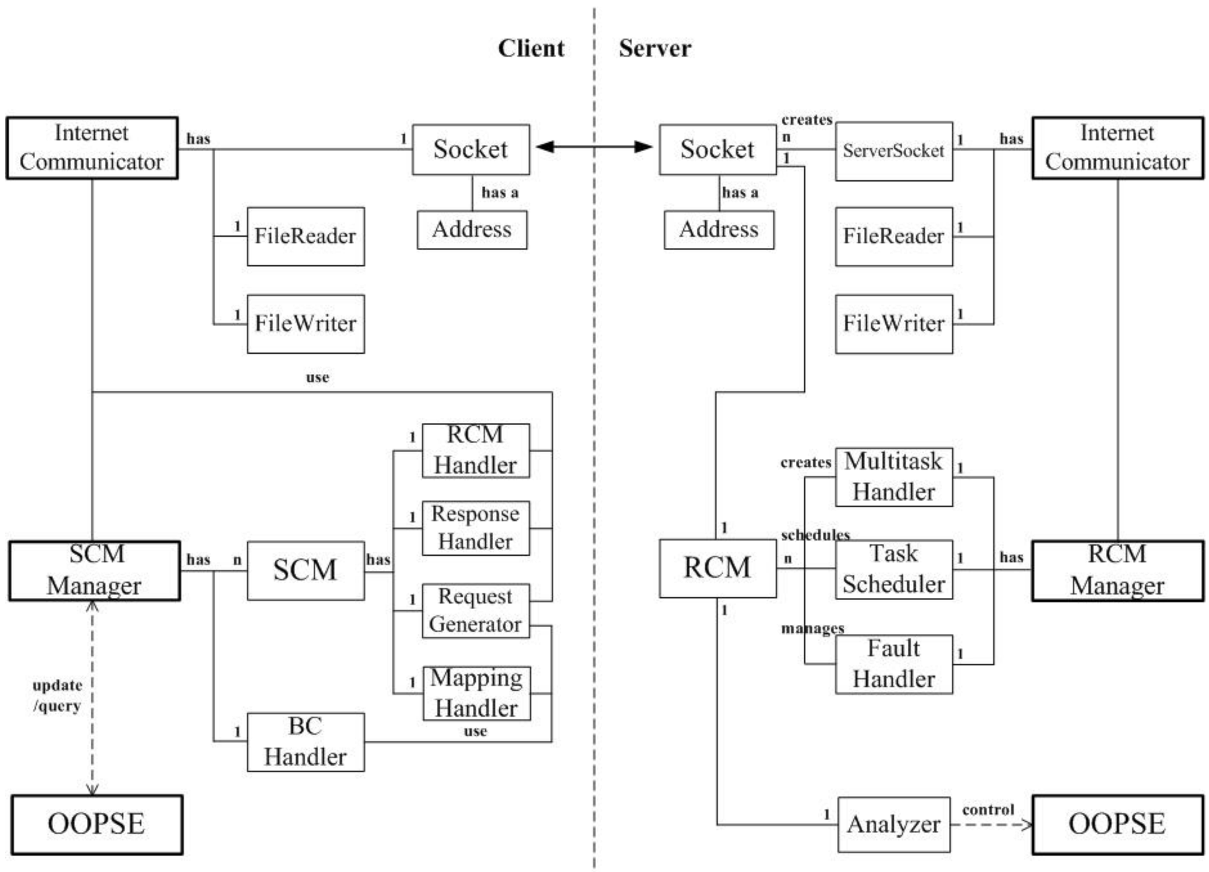

Figure 3: The object model of the core analysis module

GRAPHICAL USER INTERFACE MODULE

The graphical user interface module provides a 3D graphical and interactive interface to users for creating, managing, and viewing simulation results from a multi-level hierarchical model, which is distributed amongst clusters, from the top-most interface computer. It is a multi-window system, which will open two windows for each submodel (global or component) in the modeling hierarchy. One window is for pre-processing, and the other is for post-processing. The object model of the graphical user interface module is shown in Figure 4.

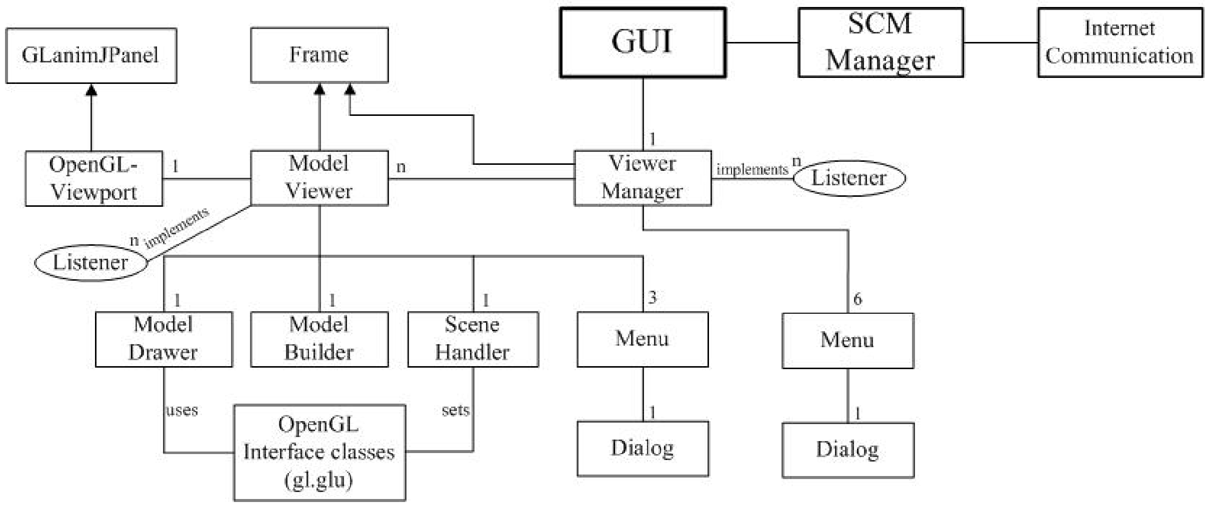

Figure 4: The object model of the graphical user interface module

NUMERICAL STUDY

The simulation of a simple two-level hierarchical model of a frame structure is presented to demonstrate the proposed system. This two-level hierarchical frame model is shown in Figure 5. The global model is a 2D 5-story frame structure. It is modeled using hinged-beamcolumn elements for its beams and columns, and pushover analysis is performed by applying triangular horizontal loads. The left-most column on the second floor is the component picked to be analyzed in detail by the rigorous model, which is modeled using fine meshes consisting of CST elements, for stress analysis. The nodal displacements of the simplified model in the global system are extracted and translated into nodal displacements on corresponding planes in the rigorous model as known boundary conditions to obtain the detailed responses of this component. The simulation of this two-level hierarchical frame model using the proposed system is shown in Figure 6.

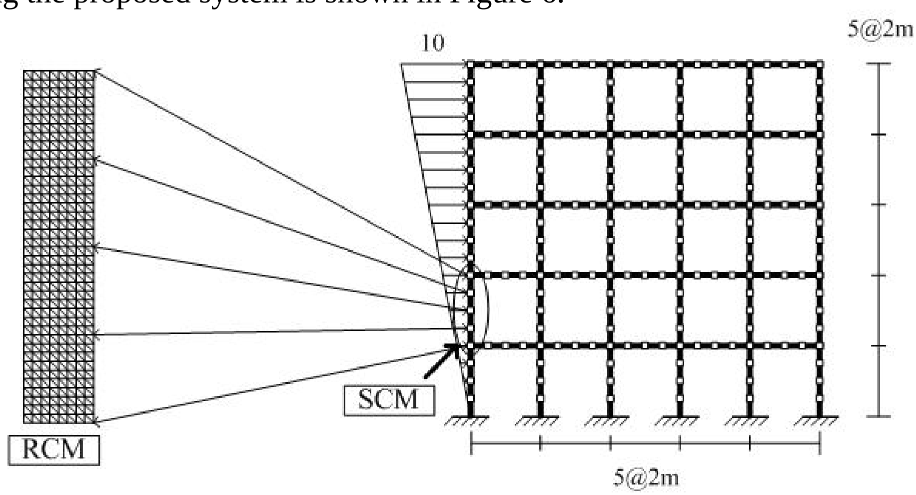

Figure 5: The two-level hierarchical frame model

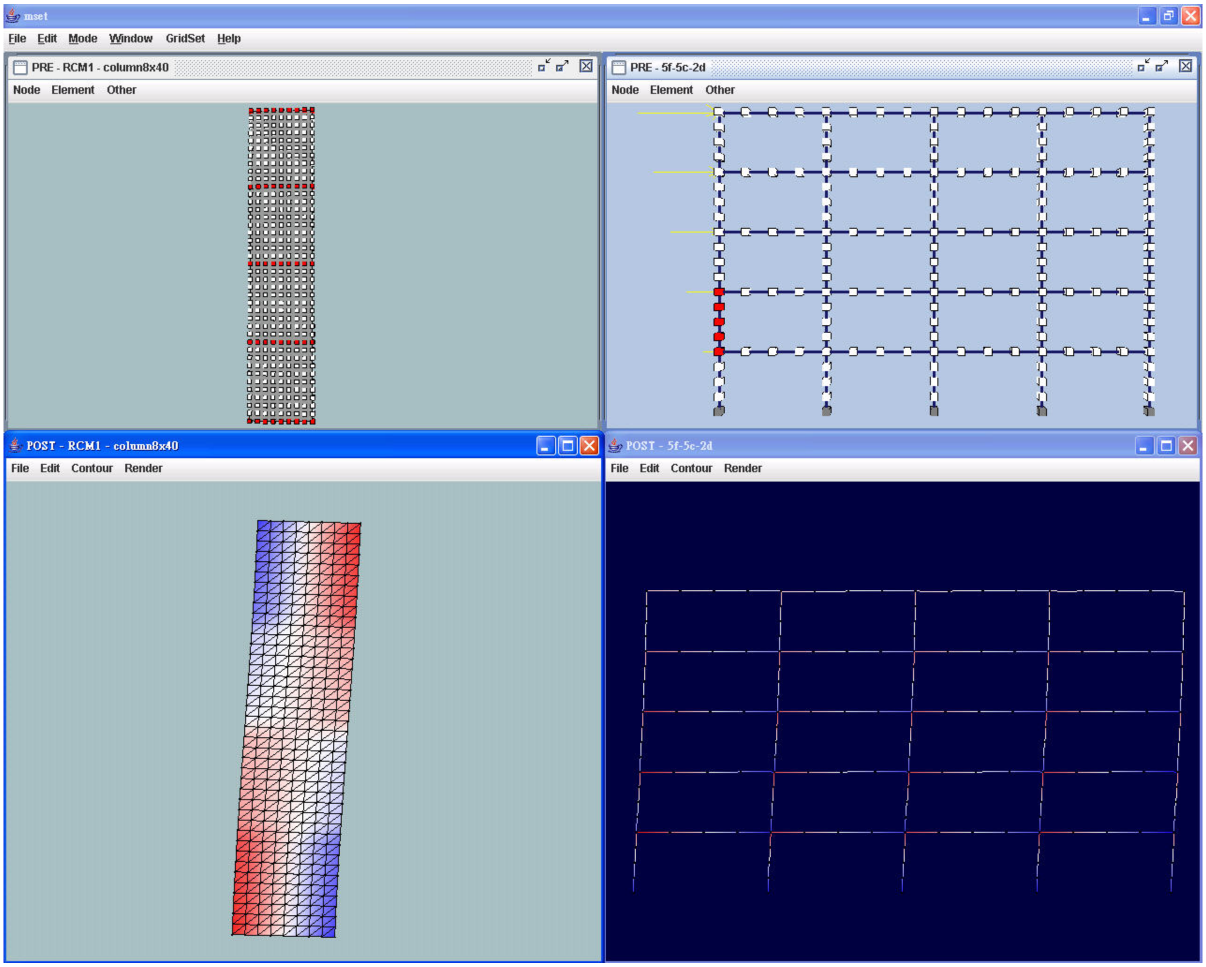

Figure 6: Simulation of the two-level hierarchical frame model using the proposed system

CONCLUSIONS

This paper has presented a grid-based structural simulation framework by integration of cluster-to-cluster distributed computing environment and multi-level hierarchical modeling and simulation. The purpose of this study is to use the Internet as a vehicle to integrate an enormous amount of computers for providing computing power needed for realizing large-scale structural simulations. Slow Internet communication is expected to be a significant bottleneck. To conquer this Internet-imposed obstacle, the grid computing environment is first organized as a two-level parallelism platform, which involves local cluster computing and remote cluster to cluster computing. Then we further developed the necessary hierarchical modeling approach and computational procedures for the proposed cluster-to-cluster computing environment to avoid the Internet communication overhead. To fulfill the proposed concept, a prototype software system to perform the proposed multi-level hierarchical modeling and simulation in a cluster-to-cluster distributed computing environment has been designed and implemented.

ACKNOWLEDGMENTS

This research was supported by the National Science Council of Taiwan under Project Number NSC 94-2211-E-011-021.

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