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PARALLEL PROCESSING OF NONLINEAR DYNAMIC ANALYSIS OF STEEL FRAME STRUCTURES USING DOMAIN DECOMPOSITION

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SUMMARY

A strategy is presented for the solution of the fully nonlinear transient structural dynamics problem in a coarse-grained parallel processing environment. Emphasis is placed on the analysis of three-dimensional framed structures subjected to seismic loading. Concerns include long-duration dynamic loading, geometric and material nonlinearity, and the wide distribution of vibrational frequencies found in frame models. The implicit domain decomposition method described employs substructuring techniques and then a preconditioned conjugate gradient algorithm for the iterative solution of the reduced set of unknowns along the substructure interfaces. The algorithm is shown to provide effective speed-up in parallel.

INTRODUCTION

Nonlinear transient analysis of structures subjected to dynamic earthquake loading provides vital information for design and research. As a research tool, nonlinear dynamic analysis provides valuable insight into the full-range behavior of frame structures. For example, it is clearly necessary for predictions of limit states and for the assessment of the onset and accumulation of structural damage. As a design tool, nonlinear analysis techniques may be used in the final stages of seismic design evaluation of important structures to insure both the integrity of a structure under moderate loadings and adequacy of energy dissipation mechanisms for its survivability under extreme loadings.

Parallel processing environments have the potential for providing significant computing power at a fraction of the cost of fourth-generation supercomputers. This paper introduces research performed on coarse-grained parallel processing of transient nonlinear structural dynamics for the simulation of three-dimensonal steel framed structures subjected to seismic loading. The domain decomposition algorithm is used for the parallel analysis. Details of the work may be found in references (1-2). The algorithm is based upon the unconditionally stable implicit Newmark-β algorithm.

The frame models used for this work consist of standard three-dimensional beam-column elements. The geometric and material nonlinear modeling adopts the approach taken by Hilmy (Ref. 3).

Finite element models of frame structures have several properties which provide particularly challenging problems when considering their implementation in parallel analysis of frame dynamics. First, nonlinearity requires frequent updating of the stiffness matrix. Second, the loading is multicomponent, nonproportional, and time-varying. More importantly, the time span of the seismic loading may be on the order of 10 to 100 times the fundamental period of the structure. Therefore, for accuracy alone, thousands of time steps must be run to model properly the nonlinear behavior.

A third property is that the modes of vibration usually range from a flexible global sway mode with a period of vibration on the order of a few seconds to exceptionally stiff modes of individual members with periods on the order of 10^{-4} to 10^{-7} seconds. This results in a condition number of 10^5 to 10^9. Neither the flexible nor the stiff modes are isolated in a particular section of the structure, but are instead distributed throughout the structure. Also, for seismic loading, only the behavior of the flexible vibrational modes needs to be considered in the solution. For conditionally stable time integration algorithms, the stiff modes force the maximum allowable time step size in the numerical integration to be far below that needed for accuracy of the modeling. For the unconditionally stable implicit algorithm considered here, the high condition number increases significantly the cost of solution of the resulting simultaneous equations using approaches that are otherwise amenable to parallelism and perform well in the solution of continuum problems.

The fourth property of frame models is that the geometry of the structure may be arbitrary, which eliminates from consideration several possible implicit solution algorithms appropriate for a set of simultaneous equations which have a regular structure based on periodic or simple geometry.

DOMAIN DECOMPOSITION

Implicit time integration requires the solution of a set of simultaneous equations. While significant progress is being made in the parallel implementation of direct solution methods, iterative algorithms are considered in this work since they are generally more amenable to parallel processing, and since little research has been previously done on the parallel iterative solution of coefficient matrices having condition numbers on the order of those arising in the frame dynamics problems.

To enhance the convergence of iterative algorithms, the system of equations should be preconditioned to reduce the condition number of the coefficient matrix. Research has indicated that domain decomposition is an effective preconditioner for iterative algorithms, including for systems having properties such as in the frame dynamics problem, and it is this approach that is adopted in this research. Domain decomposition, as defined and employed in this work, essentially performs a substructuring analysis for the solution of the system of equations of the implicit formulation. In this approach, each substructure is assembled and condensed. The inter-substructure boundary solution may be solved iteratively (instead of using a direct procedure as is common in substructuring analysis). The substructure "superelement" matrices themselves are a natural choice for the preconditioner for such iterative solution. This approach is based largely on research on parallel substructuring (Refs. 4-6).

The operations of domain decomposition may be efficiently implemented in a coarse-grained distributed-memory parallel processing environment. In particular, the entire internal assembly and condensation procedure may be performed for each substructure independently. Communication is necessary to exchange information between processors during the analysis. A parallel conjugate gradient iterative algorithm is used for the solution of the substructure interface problem because the algorithm performs well for a variety of applications and is amenable to parallel processing. Excluding the calculations required for preconditioning, the conjugate gradient algorithm requires vector additions and subtractions, vector dot products, vector norms, and one matrix-vector multiplication per iteration. The preconditioner requires decomposition of each super-element matrix at most once per time step, and one back substitution on each processor during iteration. The algorithm is excellent for parallel processing since none of these operations are inherently sequential. Therefore, the computational load may be easily balanced between the parallel processors, and these operations are easily implemented in parallel with a minimum of communication required between processors. Also, the communication is largely between neighboring domains, and, therefore, neighboring processors.

In this work, the number of domains or substructures is always taken as the same as the number of processors employed. Therefore, the single-process domain decomposition analysis used consists of direct (Cholesky) decomposition of the full set of simultaneous equations and thus entails no iterative solution.

EXAMPLE

The parallel processing bus architecture in this work consists of one to four VAXstation II's connected by Ethernet, each with 4 megabytes of core memory. This modest hardware configuration was the only parallel system available to the authors at the time of this work. Since the communication speed for a true bus architecture may typically be a few orders of magnitude faster than a shared Ethernet, the environment used here is merely a convenient tool for investigating the effectiveness of the analysis.

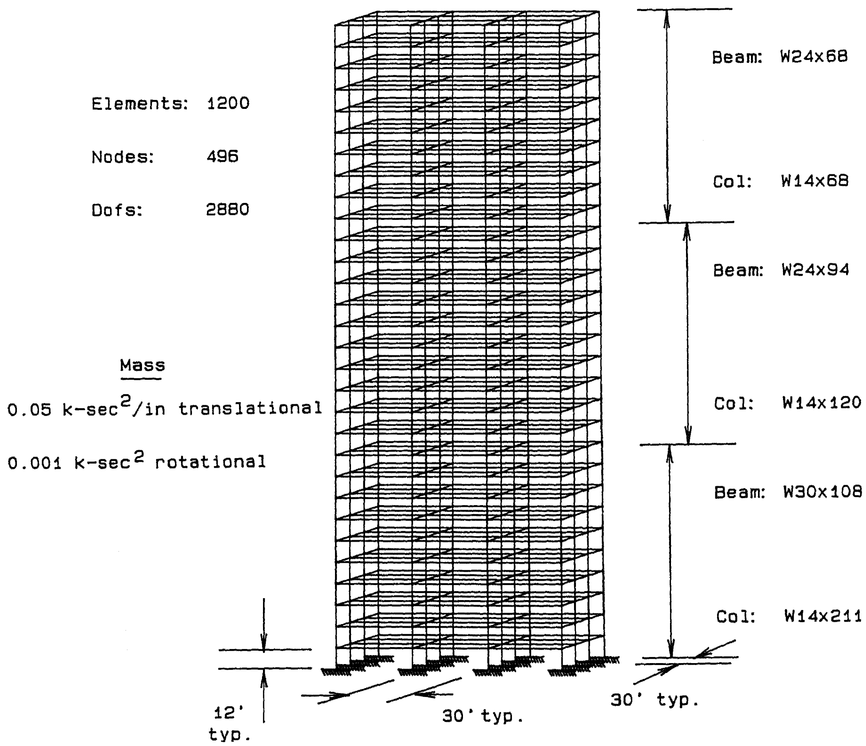

Fig. 1 Thirty-story structure used for timing and iteration count studies of the domain decomposition algorithm

One example, the 30-story frame shown in Figure 1, illustrates the potentially improved performance from using parallel processing. Details of this example, and more examples, are available in (Refs. 1-2). The structure is subjected three components of the El Centro (1940) earthquake. The time step is 0.01 seconds, and 5 seconds of the earthquake are analyzed. The analysis is run with both three and four processors, and the structure is divided as shown in Figure 2.

The total time for analysis, T_t, may be divided into computation time, T_p, and communication time, T_c. These three times for the fully nonlinear analyses on one, three, and four processors are given in Table 1. The average number of conjugate gradient iterations, and the number of degrees-of-freedom along the substructure interface are given as well. Two indicators of the performance of the parallel analysis also shown in the table are efficiency and speed-up. Efficiency is defined as the ratio of the computation time to the total time. Ideally, one would like a parallel environment which allows 100% efficiency (i.e., in which the communication time is zero). Speed-up is defined as the total time required for solution on a single-processor divided by the total time required for solution on N_p processors. Based on these definitions, a relation may be established (Ref. 2) which, for a given level of communication efficiency, predicts the speed-up on N_p processors given the computation time required for solution on N_p processors and the total time required for solution on one processor.

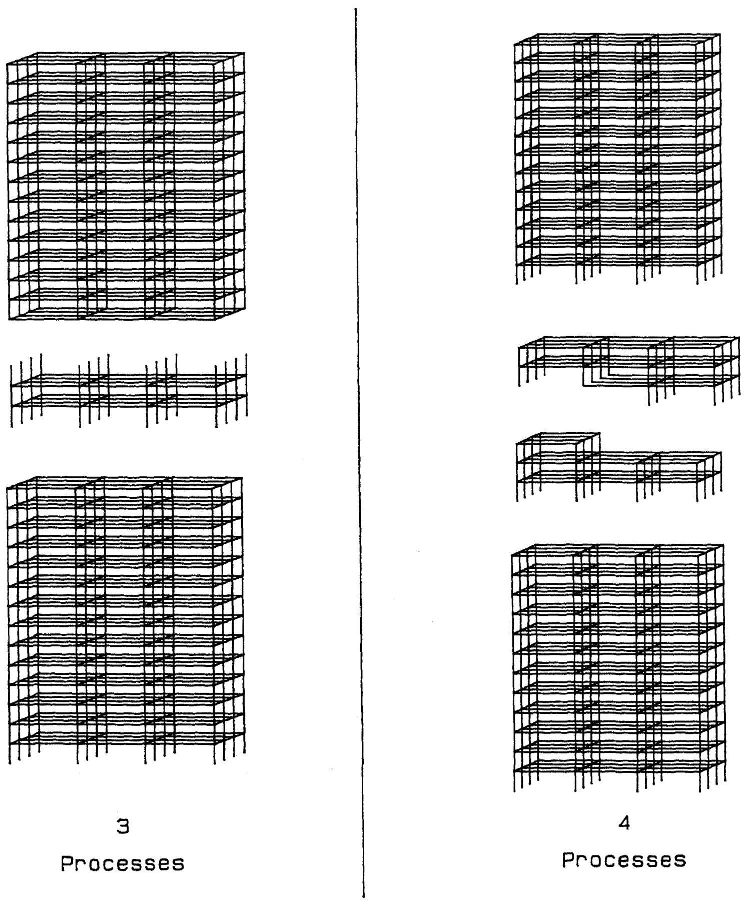

Fig. 2 Domain division of the 30-story structure

Table 1 Timing statistics for analyses of the 30-story structure using the domain decomposition algorithms (times are in days:hours:minutes: seconds)

N_p	T_t	T_p	T_c	E (%)	S	Aver. #iter.	# dofs on bou.
1	3:13:12:33	-	-	-	-	-	-
3	1:03:01:11	17:28:50	9:32:21	64.7	3.15	46	192
4	1:04:15:31	16:23:50	11:51:41	58.0	3.02	50	288

Figure 3 plots the speed-up ratio using the measured results. The speed-up ratio for an analysis running in a hypothetical environment having 100% efficiency is also shown. Since this speed-up is greater than linear, linear speed-up may be obtained on a realistic parallel hardware architecture which provides a more favorable communication rate than the system used in this work. This is indicated by the interpolated curves in the figure for efficiencies ranging from 70% to 95%. The superlinear speed-up is attained because the parallel conjugate gradient algorithm proves to be more effective (i.e., requires fewer operations) than the direct Cholesky decomposition procedure used during the single-process

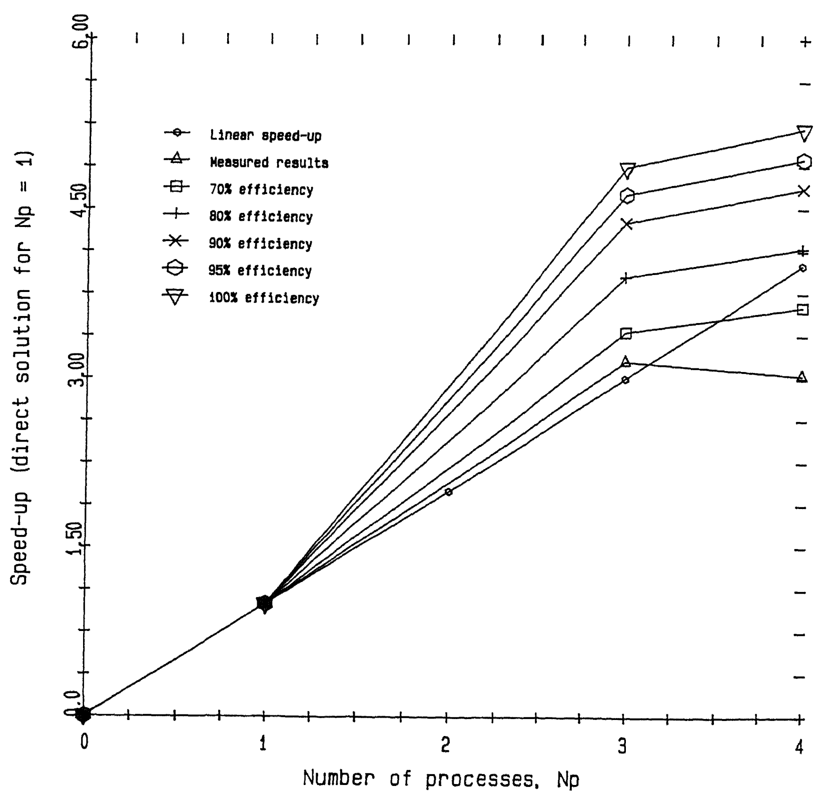

Fig. 3 Speed-up ratios for the 30-story structure using the domain decomposition algorithm

analysis. Moreover, the necessity for utilization of virtual memory for the N_p = 1 solution for this large problem contributes to the large speed-up.

CONCLUSIONS

The domain decomposition algorithm provides an efficient means for solving the fully nonlinear transient structural dynamics problem in parallel. The natural preconditioner which arises from substructuring analysis effectively reduces the condition number of the interface coefficient matrix sufficiently to allow an iterative conjugate gradient algorithm to be used for its solution. The iterative algorithm may be easily streamlined for parallel processing since it consists exclusively of vector operations.

The performance of the domain decomposition algorithm should improve considerably for the problems that are larger than were tested in this work. In particular, the algorithm tends to be more efficient as the ratio between the number of interior degrees-of-freedom and the interface degrees-of-freedom in each substructure increases. This implies that the algorithm is suitable for coarse-grained architectures and that, for a given problem, there is an optimal number of processors.

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