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Cost-Effective Use of Minicomputers to Solve Structural Problems

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In the past, large, expensive computers were required to perform most calculations in the aerospace industry. Today, low-cost minicomputers (both 16- and 32-bit) offer significant capability and are finding increased use, particularly for calculations requiring interactive response or interactive display of results. The advent of virtual memory on minicomputers was the turning point. Now minicomputers have operating system and software capabilities often surpassing those of large, mainframe computers. Minicomputers can solve any problems which can be solved by large computers, except those requiring an expensive (but faster) central processing unit (CPU) and more than 64-bit accuracy. Finite-element structural calculations are often one of the biggest challenges to large mainframe computers. This paper shows how even finite-element structural calculations can be solved cost-effectively on a minicomputer.

Introduction

MINICOMPUTERS are receiving increased use throughout the aerospace industry. This paper explores their application to solve structural problems. Until recently, minicomputer use focused primarily on process control and numerically controlled tooling applications, while their availability and opportunity for use in structural calculations has been limited. With the increased availability of this computer hardware, the question arises as to the feasibility and practicality of carrying out comprehensive structural analysis on a minicomputer. This paper presents results on the potential for using minicomputers for structural analysis by 1) selecting a comprehensive, finite-element structural analysis system in use on large, mainframe computers; 2) implementing the system on a minicomputer; and 3) comparing the performance of the minicomputer with that of a large, mainframe computer for the solution to a wide range of finite-element structural analysis problems.

Structural Analysis Capability

This section briefly describes the finite-element structural analysis system, SPAR,[1] used to carry out the analyses in the present study. Included is a summary of the capabilities of the mini- and mainframe computers that were used and the steps taken to implement, test, and evaluate the structural analysis capability on the minicomputer.

SPAR Finite-Element System

The SPAR system was selected for this minicomputer study primarily because of its efficiency in solving large structures problems on UNIVAC 1100 and CDC CYBER computers. The SPAR system performs stress, buckling, vibrations, and thermal analyses of large, linear, finite-element structural models (some exceeding 50,000 degrees of freedom), while minimizing processing cost, execution time, central memory storage, and secondary data storage through the use of sparse matrix solution techniques and advanced data management procedures.[1]

Figure 1 shows the major components of the SPAR system for two software architectures: 1) CDC and 2) UNIVAC and minicomputer. In contrast with many data files used in conventional finite-element sytems, Fig. 1 shows how the 26 SPAR processors (programs represented by 5 selected boxes) store and retrieve information and communicate with each other through a unified data base. The SPAR system is not a fixed "black box" program, but rather a package of general-purpose matrix, data base, and analysis utilities which permit significant user control and flexibility in solving problems. One example of such control and flexibility is the built-in capability for users to modify control parameters (i.e., iteration and convergence controls) at the initiation of calculations in each processor. This capability reduces unnecessary calculations and permits users to adjust parameters based on results just computed.

The SPAR system contains approximately 35,000 lines of FORTRAN source code and operates in both interactive and batch computing environments. Such features as free field input, automated grid and mesh generation, multiple coordinate systems, data base and interactive graphics utilities, early estimates of computational expense, and user control over both the amount and format of output, make the interactive mode the preferred environment for the solution of most problems. These and other features mean that data input to SPAR can be minimal even for many large structures problems. Section properties (moments of inertia, area, shear stiffness and torsion constants, principal axis orientation, and

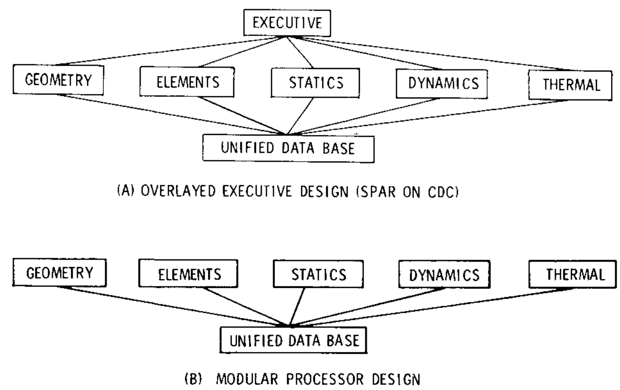

Fig. 1 Finite-element software architectures.

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shear center location) can be computed by SPAR based on section dimensions for many sections (wide flanges, boxes, tube, angles, zees, channels, and tees) if the user does not choose to input them directly.

The SPAR structural element library includes a very general class of beam elements (offsets for shear center and centroid, effects of transverse shear stiffness, and nonuniform torsion), 3- and 4-node plate/shell membrane and bending elements (isotropic, anisotropic, or composite laminate), and 6- and 8-node brick (three-dimensional) elements. Allowed loadings include point forces or moments at joints (in "oblique" directions, if required), temperatures, or pressure. A number of other important features (documented in Ref. 2), together with ongoing system enhancements, and a set of 16 test problems (which exercise a large proportion of the capabilities) make the SPAR system an ideal candidate for implementation on a minicomputer.

Computer Hardware

A CDC CYBER 173 (NOS 1.2 operating system) was used for the mainframe calculations. This system has 131,072 60-bit words of real memory and a large number of disk storage devices. A PRIME 400 was used for the minicomputer calculations (see Fig. 2). The minicomputer configuration has 196,608 16-bit words of real memory, two 40 million word disks, and virtual memory capability (each user may address one million words). Currently in the Langley installation, seven high-speed (4.8-9.6 Kilobaud; 1KB = 1000 bits/s) data lines link Tektronix 4014 terminals to the minicomputer. A 4.8 KB mainframe link permits any terminal user with one

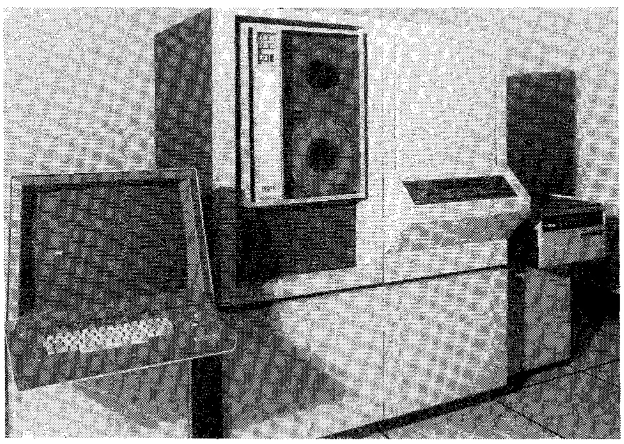

Fig. 2 PRIME 400 minicomputer with a Tektronix 4014 graphics terminal.

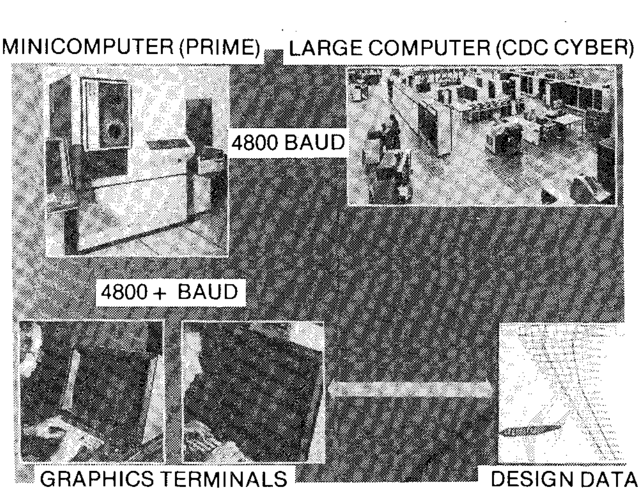

Fig. 3 Interactive terminal access to mini- and mainframe computers.

command to transfer computations from the minicomputer to the mainframe dark lines (Fig. 3). The results of mainframe computations are automatically returned to a file in the user area on the minicomputer from where the command was issued. Following implementation of SPAR on the PRIME 400, it was installed and tested on a PRIME 300 to assure that it would operate on a smaller minicomputer (described in Ref. 4). The cost of the mainframe computer is several million dollars; the cost of the large minicomputer system is approximately $150,000; the cost of the smaller minicomputer is approximately $90,000. For subsequent cost comparisons, one hour of CPU time on the mainframe and minicomputer are $600 and $15, respectively, which approximate current charges.

SPAR Implementation on a Minicomputer

To the authors' knowledge, a comprehensive finite-element system comparable to SPAR has never been implemented previously on a minicomputer. Converting the SPAR system from CDC to PRIME was accomplished expeditiously via interactive terminals using the mini-mainframe link (Fig. 3) and the comprehensive text edit, trace, and debug utilities available on the minicomputer. The following is a summary of the steps involved in implementing SPAR on the minicomputer through minimal changes to the original source code and by making input and user interface nearly identical to that for UNIVAC and CDC computers. This procedure resulted in a first-level working version of SPAR on the minicomputer, which is continually being upgraded to improve efficiency and completeness.

The first step was to eliminate the primary overlay (executive in Fig. 1a) of the CDC version of SPAR and implement the configuration shown in Fig. 1b. This was accomplished by moving the data handling software of the executive to a subroutine library on the minicomputer. This approach (Fig. 1b) also eliminated the need to redo the system for each new processor added. Direct disk-memory operating system routines are used for data transfer for SPAR on UNIVAC computers and similar COMPASS code used for the CDC implementation. FORTRAN equivalents of these six routines were written for the minicomputer version. A number of routines to support new SPAR "interactive graphics processors" for the minicomputer were also included in the data base library.

The second step was to implement 26 SPAR processors as separate programs which communicate with each other via the SPAR data base (Fig. 1). Typical changes to the CDC version of SPAR that were required to implement the processors on the minicomputer dealt with compiler and operating system differences. Substitutions were made for some Hollerith data using 60-bit words, octal constants, and COMPASS routines. Dynamic memory allocation (used in the CDC version of SPAR), whereby the working data space (COMMON) is positioned "above" the program, was also implemented in the minicomputer version. This important feature permits the size of problems that can be solved to be a function of the computer hardware rather than the program. For simplicity of implementation, 32-bit integers were used for all processors, except graphics, in the minicomputer version, although increased use of 16-bit integers is planned to improve performance. A minicomputer routine was developed which permits flexible input/output from and to disk files and/or interactive terminals. After a procedure was established to report on differences between mainframe and minicomputer systems, the engineering time to implement a SPAR processor on the minicomputer varied from five minutes to several hours, depending upon processor complexity.

Finally, the complete set of 16 SPAR test problems[2] was run on the minicomputer version which, when compared with equivalent mainframe results, uncovered needed changes to several output format statements and convergence criteria.

Differences in performance between the mini and mainframe version were noted and are discussed in the Results section. Also, performance of some of the SPAR processors was evaluated on the smaller minicomputer. Such installation of SPAR on even smaller minicomputers is possible since the executable processors of the minicomputer version of SPAR occupy only a small fraction (less than 10%) of a small (1.5 million word) disk. Further checkout included use of a preliminary version of the SPAR mini capability by structural researchers at three other sites. The final SPAR mini version is available from the Computer Software Management and Information Center, Athens, Ga., the distribution center for NASA software.

Results

To assess the potential of minicomputer-based structural analysis, the 16 test problems plus two other problems were solved using SPAR on both the mini and mainframe computers. Calculations were done via separate 0.3 and 4.8 KB lines, respectively, for the mainframe and minicomputer as shown in Fig. 3. The problems ranged from a small beam problem (11 nodes, 10 elements, 60 degrees of freedom) to a model of a launch umbilical tower (2208 degrees of freedom, Fig. 4). The 16 test problems are described in detail in Ref. 2, which includes an annotated list of input, representative plots, contents of the SPAR data libraries and, where possible, comparisons with analytical solutions. These SPAR demonstration problems cover a wide range of static, dynamic, and buckling results and served as useful checkout and performance benchmark problems for SPAR on the minicomputer. Many of these problems also include subproblems; i.e., the 11-node beam problem includes the static, dynamic, and buckling analysis due to a number of static and thermal loadings. In addition to the 16 SPAR demonstration problems, results were obtained on both computers for the static analysis of a 450-node wing model of a current NASA flight project (Fig. 5), and a 63-node large area space structure (Fig. 6). Figures 4-6 were produced in approximately 1 min each at an interactive terminal by a new plot processor of the SPAR mini version.

Figure 7 compares the CPU time required on both computers for solving the beam problem. In all stages of the analysis (input, stiffness, and solution), the figure shows the mainframe CPU time (stippled) to be 3-4 times less than the minicomputer CPU time using virtual memory (dashed). The greater CPU time required on the minicomputer is due to its relatively slow execution speed. Other reasons include the use of long integers (32-bit) on the minicomputer, rather than its basic hardware design (16-bit), the use of FORTRAN throughout on the mini (faster COMPASS routines were used on mainframe), and the inclusion of some disk activity in the minicomputer times.

Of more importance than CPU time to the engineering user, however, is the elapsed time for calculations, i.e., the total time between job submittal and availability of results. Figure 8 shows the minicomputer elapsed times for the 18 problems as a function of their size (degrees of freedom). The minicomputer elapsed times are normalized with respect to the mainframe computer times obtained under a normal workload. Only the best times are shown for the mainframe, as in some cases of heavy usage, the mainframe times were considerably greater than shown. The majority of problems executed in less than three minutes CPU time and one hour elapsed time on the mainframe.

Figure 8 shows that for 12 smaller problems, the minicomputer returned results quicker than the mainframe computer. The results shown in Fig. 8 are, of course, installation dependent and, in particular, are significantly influenced by the load on each computer. Nevertheless, the results show that it is possible to solve realistic finite-element problems on a minicomputer which supports a moderate

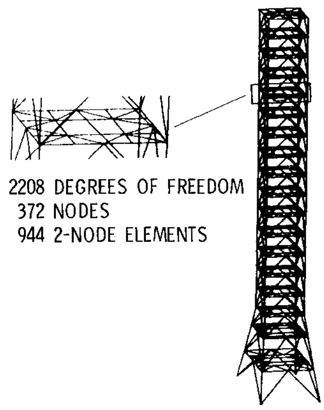

Fig. 4 Launch umbilical tower model.

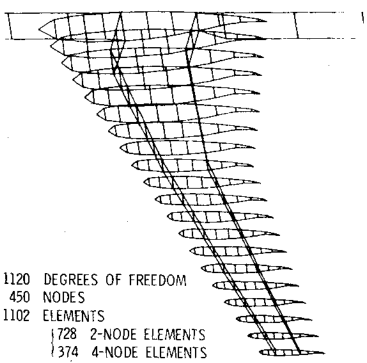

Fig. 5 Finite-element wing model.

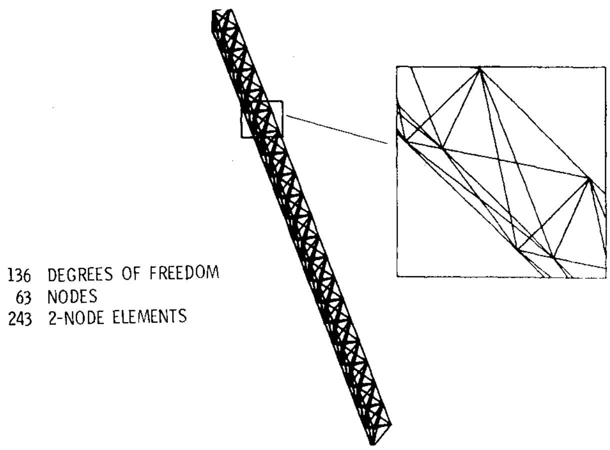

Fig. 6 Large area space structure component.

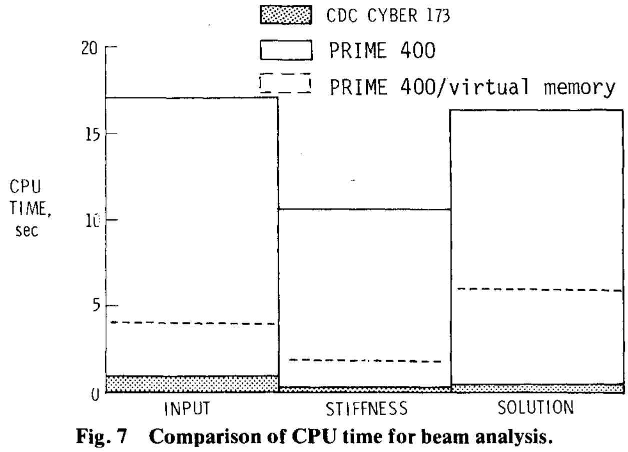

Fig. 7 Comparison of CPU time for beam analysis.

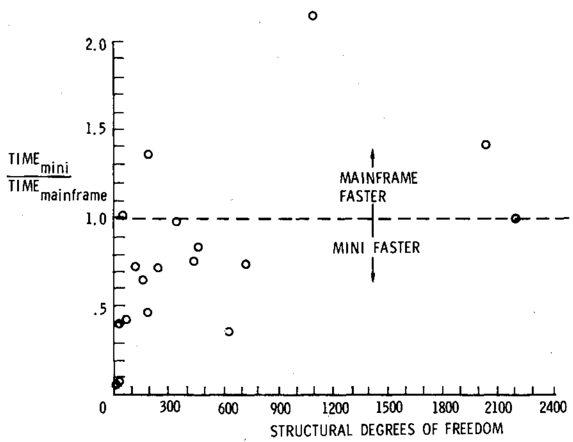

Fig. 8 Comparison of elapsed time vs problem size.

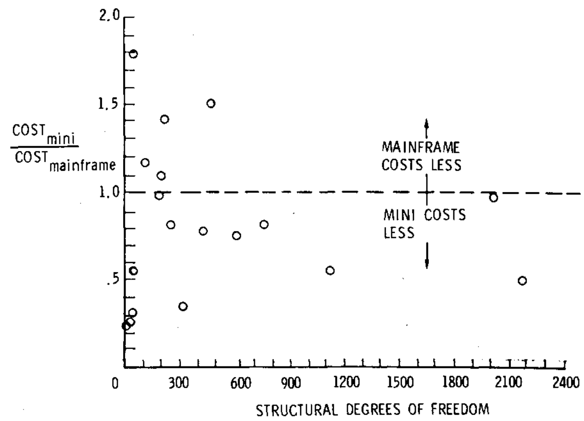

Fig. 10 Comparison of computing cost vs problem size.

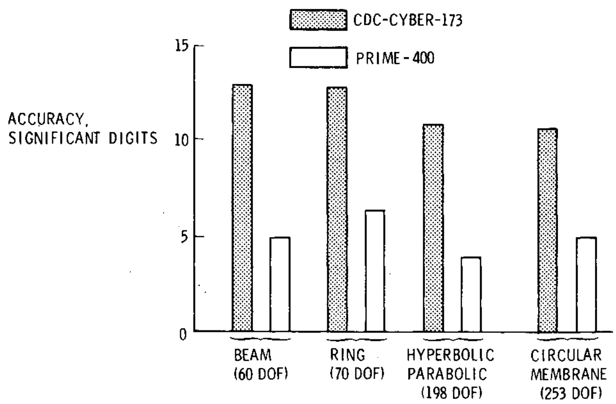

Fig. 9 Comparison of accuracy vs problem size.

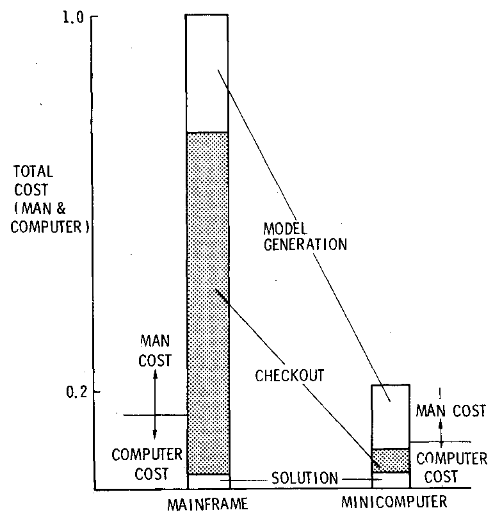

Fig. 11 Comparison of total cost (man + computer).

number of users (4.8 KB) in approximately the same elapsed time as that required for a large computer supporting the usual large number of users (0.3 KB).

Figure 9 shows typical accuracy of displacement results for five selected problems for both computers. The number of significant digits of accuracy for displacements is shown on the ordinate vs the problem size on the abscissa. The displacements u produced by the minicomputer and mainframe were compared, and the accuracy found to agree with the reciprocal of the cumulative error: $(F^Tu-u^TKu)/F^Tu$ calculated by SPAR where K is the stiffness matrix and F^T the transpose of the forces. Figure 9 shows the accuracy obtained on the minicomputer to be less than for the mainframe computer, but that four-place accuracy is possible on the minicomputer for single precision and even more for double precision.

Figure 10 shows the relative computational cost for the benchmark problems on both the minicomputer and the large mainframe computer. The figure shows the minicomputer computations to cost somewhat less than those of the mainframe for all but five of the benchmark problems with an average saving of 20%. The problems used more CPU time on the minicomputer, but the CPU cost of the minicomputer is only a fraction of the mainframe cost, resulting in the cost savings shown. Also, the accuracy on the minicomputer (4 places) is not as great as that of the mainframe (10 places). Current work on improving the efficiency of SPAR on the minicomputer[3] should significantly reduce both the minicomputer costs (Fig. 10), the CPU and elapsed times (Figs. 7 and 8), and increase accuracy (via double precision).

The installation and operation of SPAR on the smaller minicomputer was successful and the performance acceptable, although noticeably less than for the larger minicomputer. In addition, for large problems, a minicomputer mainframe network with linked SPAR data bases could have high potential to maximize the features of both machines in solving structures problems.[3]

The total cost of accomplishing work includes not only computer cost but engineer costs as well. A typical structure shown in Fig. 6 was analyzed according to its total cost (including both engineering and computer time). The results in Fig. 11 illustrate the relative total costs for the two computers in the areas of model generation, checkout, and solution. The figure shows the minicomputer to be cost-effective for model generation and checkout, and the mainframe to be cost-effective for large "number crunching." The lower costs for the minicomputer are attributed to its performance characteristics, including high communication rate, interactive graphics, ease of use, and good response.[4] Engineering time is dominant in Fig. 11, and the minicomputer significantly reduced it. It is conceivable that even very large problems could be solved by SPAR on the minicomputer if the accuracy and calculation speed of a mainframe is not required.

Concluding Remarks

This paper shows the feasibility and potential to solve structural analysis problems on a minicomputer. Results are presented which show the performance and cost benefits of using minicomputers to solve structures problems. A comprehensive finite-element system (for stress, buckling, vibration, and thermal analyses) is described and the steps taken to implement the system on a minicomputer briefly discussed. Results from 18 benchmark problems (36-2208 degrees of freedom) are given which show the performance and cost-effective advantages offered by the minicomputer.

The CPU time used to solve the benchmark problems on the minicomputer is shown to be, as expected, significantly greater than corresponding times on the mainframe. The accuracy of solutions on the minicomputer was four places for most problems, as compared to 8-13 places on the large mainframe. The elapsed (wall clock) time to complete computations was approximately the same for both computers. Computer operation cost savings occurred for most problems through use of the minicomputer with the average saving of approximately 20%. The overall man-machine cost reduction for a typical problem was approximately 80% using the minicomputer.

All the results shown are for the initial SPAR minicomputer version, and efficiency improvements are currently underway which should significantly reduce the CPU times, elapsed times, and costs, making minicomputer use even more attractive. For large problems, where the CPU time may be extremely long on the minicomputer, a linked minicomputer-mainframe network could have high potential to maximize the features of both machines.

In view of the low initial and operating costs of the minicomputer and the increasing user-oriented software available in minicomputers, this study suggests that minicomputers can meet many of the needs for analysis of moderate size structural problems. Increased use of minicomputers should be cost-effective for a small size office working environment or in engineering departments within larger organizations. They may even serve engineers to perform major parts of the analysis and design work of the future.

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