Optimization of Large Space Frame Steel Structures

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ABSTRACT

Optimization of large space frame steel structures subjected to realistic code-specified stress, displacement, and buckling constraints is investigated. The basis of design is the American Institute of Steel Construction (AISC) Allowable Stress Design (ASD) specifications. The types of structures considered are space moment resisting frames with and without bracings. The structures are subjected to wind loadings according to the Uniform Building Code (UBC) in addition to dead and live loads. The parallel-vector algorithm developed in this research is applied to three highrise building structures ranging in size from a 20-story structure with 1,920 members to a 60-story structure with 5,760 members, and its parallel processing and vectorization performance is evaluated. For the largest structure, speedups of 6.4 and 17.8 are achieved due to parallel processing (using eight processors) and vectorization, respectively. When vectorization is combined with parallel processing a very significant speedup of 97.1 is achieved.

INTRODUCTION

Most of the structural optimization algorithms presented in the literature are applied to small structures or academic examples with simple constraints (Adeli, 1993). The true advantage of the optimization technology is realized only when it is applied to large structures. High-performance multiprocessor computers provide an unprecedented opportunity to apply optimization technology to design of large structures with thousands of members subjected to realistic code-specified design constraints. The challenge is to develop efficient algorithms employing the unique architecture of these machines (Adeli and Kamal, 1993).

The goal of this research is to develop efficient and robust parallel-vector algorithms for optimization of large space steel structures subjected to the actual design constraints of the American Institute of Steel Construction (AISC) Allowable Stress Design (ASD) specifications (AISC, 1989). Some of the AISC ASD constraints are highly nonlinear and implicit functions of design variables, specially in the case of moment-resisting frames. This can create convergence and stability problems and increase the CPU requirement significantly, specially for large structures.

We first formulate an optimality criteria approach for optimization of steel structures subjected to stress, displacement, and buckling constraints of the AISC ASD specifications. Two different scaling procedures are used, one suitable for space axial-load structures, and the other suitable for space moment-resisting frames. Then, the parallel-vector structural optimization algorithm is described briefly. Next, the algorithm is applied to minimum weight design of three space moment-resisting frames. Finally, the performance of the algorithm is evaluated by presenting speedup results for parallel processing and vectorization.

AN OPTIMALITY CRITERIA APPROACH

The general structural optimization problem with design linking strategy can be stated in the following form: Find the set of design variables, A_i (cross sectional areas), such that the weight of the structure

$$W = \sum_{i=1}^{N_d} \rho_i A_i \sum_{m=1}^{N_{mi}} L_{im} \tag{1}$$

is minimized subject to the constraints of the AISC ASD specifications to be described shortly. In Eq. (1)

N_d = number of design variables (groups of members with identical cross sections)
L_{im} = length of member m belonging to group i
ρ_i = unit weight of members in group i
N_{mi} = number of members in group i
A_i = cross sectional area of members in group i

The displacement and fabricational constraints are:

$$r_j^L \le u_{jk} \le r_j^U, \quad j = 1, ..., N \quad k = 1, ..., L \tag{2}$$

$$A_i^L \le A_i \le A_i^U, \quad i = 1, ..., N \tag{3}$$

where

k = loading number

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N = total number of displacement degrees of freedom
L = number of loading conditions
A_i^L = lower bound on the cross sectional area
A_i^U = upper bound on the cross sectional area
u_{jk} = displacement of the jth degree of freedom due to loading condition k
r_j^L and r_j^U = lower and upper bounds on the displacement of the jth degree of freedom.

When the beam-column member is under compression, the stress constraints are

$$\begin{cases} \dfrac{f_{amk}}{F_{am}} + \dfrac{C_{mx} f_{bmkx}}{\left(1 - \dfrac{f_{am}}{F_{ez}}\right) F_{bmx}} + \dfrac{C_{my} f_{bmky}}{\left(1 - \dfrac{f_{am}}{F_{ey}}\right) F_{bmy}} \le 1.0, \text{ for } \dfrac{f_{amk}}{F_{am}} > 0.15 \\ \dfrac{f_{amk}}{0.60 F_y} + \dfrac{f_{bmkx}}{F_{bmx}} + \dfrac{f_{bmky}}{F_{bmy}} \le 1.0 \end{cases} \tag{4}$$

$$\frac{f_{amk}}{F_{am}} + \frac{f_{bmkx}}{F_{bmx}} + \frac{f_{bmky}}{F_{bmy}} \le 1.0, \text{ for } \frac{f_{amk}}{F_{am}} \le 0.15 \tag{5}$$

where

f_{amk} = computed compressive stress in member m due to the loading condition K
f_{bmk} = computed bending stress at the point under consideration due to loading condition k
F_{bm} = allowable bending stress in member m
F_y = yield stress of the material

For compression members in unbraced frames, the value of C_m is 0.85. N_m is the total number of members in the structure which is equal to

$$N_m = \sum_{i=1}^{N_d} N_{mi} \tag{6}$$

We assume full lateral support is provided for horizontal members (beams). For columns and inclined members, we assume lateral support is provided at the ends of members only. The term F_e is defined as

$$F_e = \frac{12\pi^2 E}{23(KL_b / r_b)_m^2} \tag{7}$$

where

L_b = unbraced length in the plane of bending
r_b = radius of gyration in the plane of bending
E = modulus of elasticity of steel
K = effective length factor

The allowable bending stress is computed based on Chapter F of the AISC ASD specifications. The allowable compressive stress, F_{am}, is given as a function of the governing slenderness ratio for member m, $(Kl/r)_m$, as follows:

$$F_{am} = \begin{cases} \left\{ \dfrac{\left[1 - \dfrac{KL/r)_m^2}{C_c^2}\right] F_y}{\left[\dfrac{5}{3} + \dfrac{3(KL/r)_m}{8C_c} - \dfrac{(KL/r)_m^3}{8C_c^3}\right]} \right\} \text{ for } (KL/r)_m \le C_c \\ \dfrac{12\pi E}{23(KL/r)_m^3} \text{ for } (KL/r)_m > C_c \end{cases} \tag{8}$$

The coefficient C_c is defined as

$$C_c = \sqrt{\frac{2\pi^2 E}{F_y}} \tag{9}$$

The effective length factor, K for braced and unbraced frames is found by the approximate equations from the European steel design code (Anonymous, 1978, and Dumonteil, 1992).

Considering only the active constraints, the Lagrangian function for displacement constraints is defined as:

$$L(\lambda_{jk}, A_i) = \sum_{i=1}^{N_d} \rho_i A_i \sum_{m=1}^{N_{mi}} L_{im} + \sum_{j=1}^{N_{ac}} \sum_{k=1}^{L} \lambda_{jk}(u_{jk} - r_j) \tag{10}$$

where

λ_{jk} = positive Lagrange multiplier for displacement constraint associated with the jth constrained degree of freedom and the kth loading case
N_{ac} = number of active displacement constraints

A displacement constraint is called active when it is in the neighborhood of the limiting value within a given tolerance. Employing the principle of virtual work, the gradient of the jth displacement degree of freedom under the kth loading condition with respect to design variable A_i can be expressed as

$$g_{ijk} = \frac{\partial u_{jk}}{\partial A_i} = \sum_{m=1}^{N_{mi}} - v_{imj}^T \frac{K_{im}}{\partial A\, i} u_{imk} \tag{11}$$

where

v_{imj} = virtual displacements vector of member m belonging to group i due to the application of a unit load in the direction of the jth degree of freedom. For a space frame, v_{imj} is a 12×1 vector (three displacements and three rotations for each node of the member) and for a space truss, v_{imj} is a 6×1-vector (three displacements for each node).
K_{im} = 12×12 (6×6) stiffness matrix of member m belonging to group i for a space frame (space truss)
u_{imk} = 12×1 (6×1) displacement vector of member m belonging to group i due to the loading condition k for a space frame (space truss).

We use two different scaling procedures, one for space truss (axial-load) structures and the other for space moment-resisting frames. For space truss structures, the member stiffness matrix is a function of the cross-sectional area and we use a scaling procedure based on a combination of the maximum displacement scaling factor (SFD) and stress scaling factors for those members whose compressive stress constraints are violated (SFS's). Details of this scaling procedure are given in Soegiarso and Adeli (1996). For space frames, the member stiffness matrix is a function of not only the cross-sectional area but also the moments of inertias I_x, and I_y and the torsion constant J. Therefore, a different scaling procedure is devised, as explained in Soegiarso and Adeli (1997).

PARALLEL-VECTOR ALGORITHM

The impact of vectorization on structural optimization has been discussed in Soegiarso and Adeli (1994a). Through the judicious use of the vectorization techniques the speedup of the vectorized algorithm can reach the range 15–19. In this research, we developed a parallel-vector multi-constraint discrete optimization algorithm for optimization of large space frame steel structures. Due to space limitation, however, the algorithm itself will not be presented in this article.

In OC-based structural optimization algorithms, most of the computer processing time is spent in assembling the structure stiffness matrix, computing the gradients, and solving for the nodal displacements. Most tasks in these steps are executed in a DO loop. Parallelization at a DO loop is called Microtasking (Cray, 1991, Saleh and Adeli, 1994). The challenge is to develop algorithms where the outer DO loops can be partitioned and distributed to all processors evenly and the inner DO loops can be vectorized. In developing an efficient microtasked program it is necessary to understand how the values in the DO loop are stored. Basically, we have two kinds of storage. The first type is global storage (shared memory) where the data can be used and modified in any subroutine and passed through the Common blocks argument. The second type is the local storage (private memory) where the data are used and modified in a subroutine only. In this case, the data can not be passed to another subroutine. When the data stored in the shared memory are modified by different processors, a racing condition may be encountered resulting in erroneous results (Adeli and Kamal, 1993). To avoid undesirable results we employ the directives *Guard* and *Endguard* provided by the Cray FORTRAN compiler in a *guarded region*. In this region only one processor at a time can update the same location.

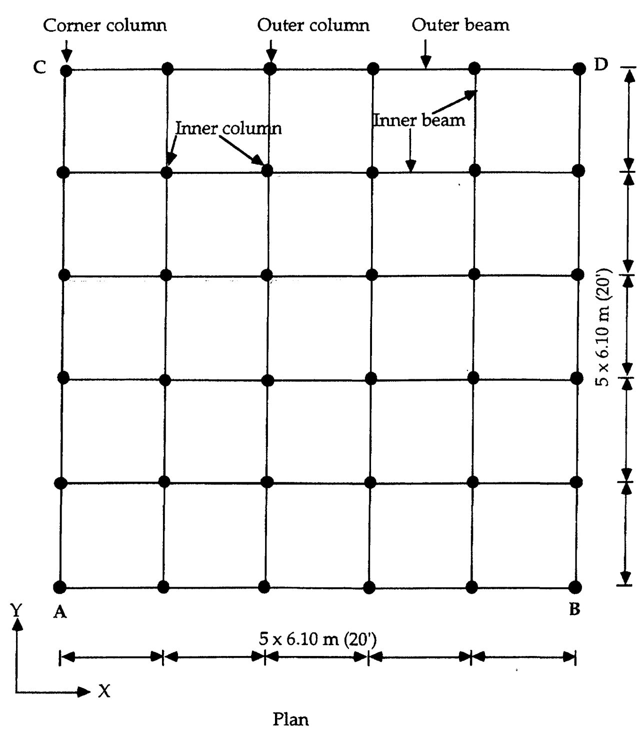

Fig. 1a. Example 1 (20-story space moment-resisting frame).

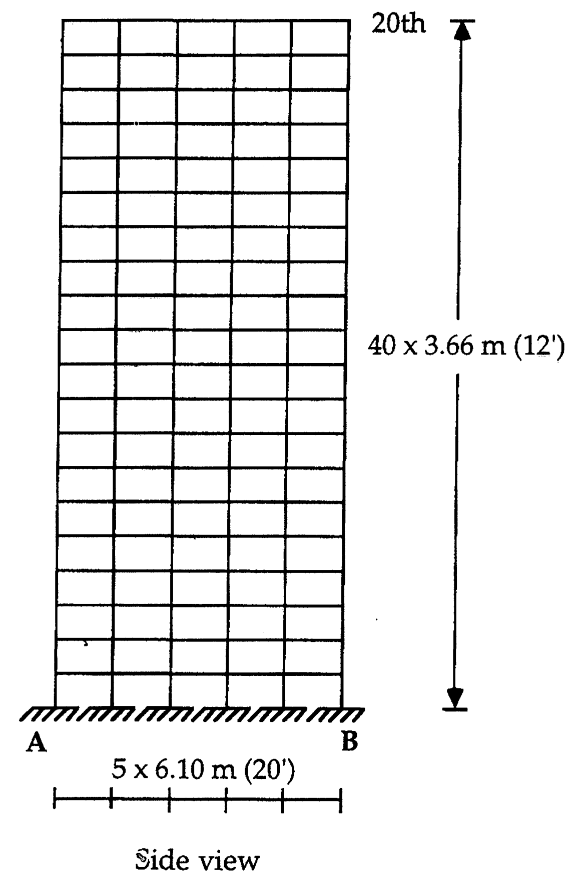

Fig. 1b. Example 1 (20-story space moment-resisting frame).

APPLICATIONS

The parallel-vector algorithm developed in this research has been implemented in FORTRAN on the Cray YMP8/864 supercomputer with eight processors. The algorithm has been used for minimum weight design of three space moment-resisting steel frames, The basis of design is the AISC ASD specifications (AISC, 1989). The data for the example structures are summarized in Table 1.

Example 1. 20-story space moment-resisting frame

This example is a 20-story space moment-resisting frame with a square plan shown in Figure 1a. The structure has an aspect ratio of 2.4. It has 756 nodes and 1,920 members divided into 100 groups of members. A wide-flange (W) shape is selected for each group. The groups are organized as follows: Columns of each story are divided into three groups, that is, a group of corner columns, a group of outer columns, and a group of inner columns. The beams of each floor are divided into two groups, outer beams and inner beams. The loading on the structure consists of dead load (*D*) of 2.78 kPa (58 psf), Live Load (*L*) of 2.38 kPa (50 psf) and Roof Live Load (Lr) of 2.38 MPa (50 psf). The horizontal loads in the X-direction at each node on the sides AC and BD are obtained from the Uniform Building Code (UBC, 1991) wind loading using the equation

$$d_p = C_e C_q q_s I$$

where

d_p = design wind pressure
C_e = combined height, exposure gust factor coefficient
C_q = pressure coefficient
q_s = wind stagnation pressure
I = importance factor

The value of C_q for inward face is 0.8 and for the leeward face is 0.5. Assuming a basic wind speed of 70 mph (113 km/h), the value of q_s is 0.6 kPa (12.6 psf) and the importance factor is assumed to be one. The values of C_e are taken from the UBC (1991) assuming exposure B. The lower and upper bounds of the cross-sectional areas in this example are 24.5 cm^2 (3.80 in.^{2}) and 683 cm^2 (106 in.^{2}). The material is assumed to be steel with modulus of elasticity of 199.9×10^3 MPa (29,000 ksi) and the unit weight of material 0.077 N/cm^3 (0.284 lb/in^3). The displacement constraints are given as ±29.26 cm (11.52 in.) in the X-direction for nodes on the top level (equal to 0.004*H*). The maximum number of iterations is set to 10. Figure 2 shows the convergence history. A minimum weight of 10.6 MN (2,395 kips) is found after 6 iterations. This translates into 0.57 kPa (12.0 lbs/ft^2) when the weight is divided by the total floor area provided by the structure.

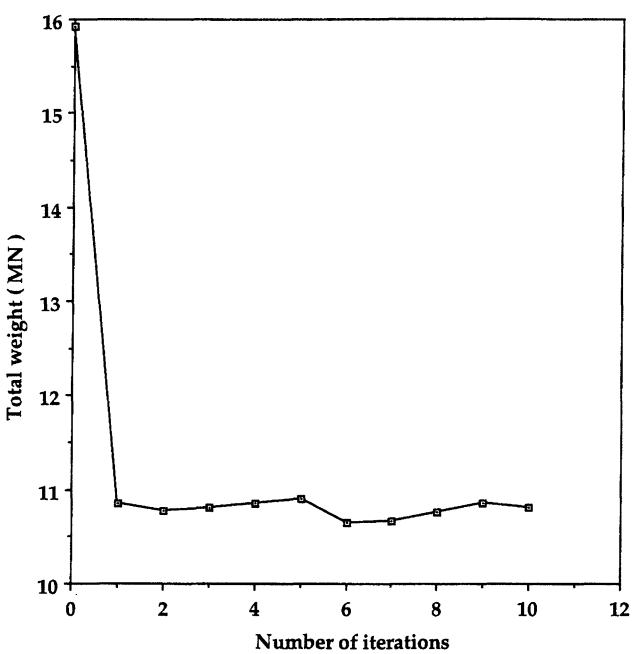

Fig. 2. Convergence history for Example 1 (20-story space moment-resisting frame).

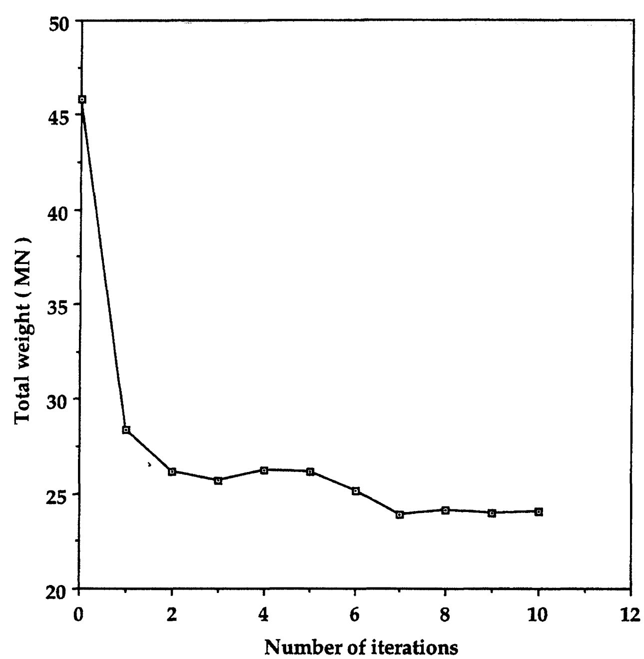

Fig. 3. Convergence history for Example 2 (40-story space moment-resisting frame).

(1) Type of structure	(2) Example	(3) NDOF	(4) No. of members	(5) Aspect ratio	(6) CPU time for vectorized code using eight processors (seconds)	(7) MFLPOS*	(8) Speedup due to parallel-ization on eight processors	(9) Speedup due to vector-ization only*	(10) Speedup due to vector-ization & parallel-ization
Space frame	1	4,536	1,920	2.4	149.46	130.1	6.10	18.10	92.70
	2	8,856	3,840	4.8	781.23	134.6	6.25	17.90	95.60
	3	13,176	5,760	7.2	1,735.00	137.3	6.37	17.80	97.10

Table 1. Performance of the Parallel-Vector Algorithm

*on a single processor

Example 2. 40-story space moment-resisting frame

This example is a 40-story space moment-resisting frame consisting of 1,476 nodes and 3,840 members. The plan of this structure is the same as that of Example 1 (Figure 1a). Its elevation is similar to that of Example 1 with the same uniform story height of 3.66 m (12 ft) but total height of 146.4 m (480 ft) giving the structure an aspect ratio of 4.8. The members are divided into 200 groups of members. A W shape is selected for each group. The groups are organized similar to Example 1. The loadings on the structure and the material properties are the same as those of Example 1. The lower and upper bounds of the cross-sectional areas in this example are 24.5 cm^2 (3.80 $in.^2$) and 1,606 cm^2 (249 $in.^2$). The displacement constraints are given as ± 58.52 cm (23.04 in.) in the

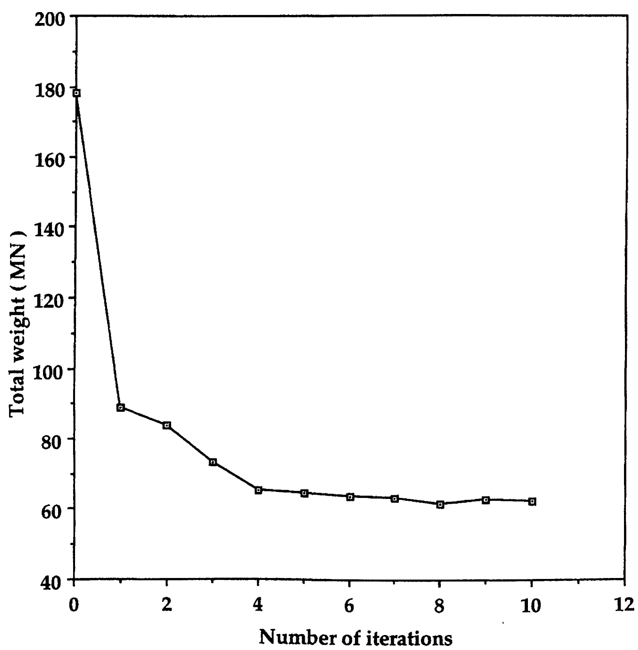

Fig. 4. Convergence history for Example 3 (60-story space moment-resisting frame).

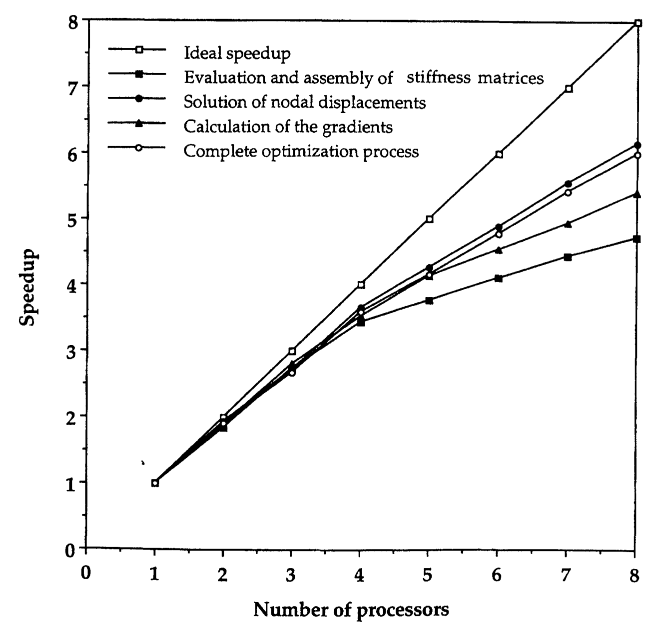

Fig. 5. Speedups due to parallel processing only for Example 1.

X-direction for nodes on the top level (equal to 0.004*H*). The maximum number of iterations is set to 10. Figure 3 shows the convergence history. A minimum weight of 23.9 MN (5,372 kips) is found after 7 iterations. This translates into 0.64 kPa (13.4 lbs/ft^2) when the weight is divided by the total floor area provided by the structure.

Example 3. 60-story space moment-resisting frame

This example is a 60-story moment-resisting frame consisting of 2,196 nodes and 5,760 members. The plan of this structure is the same as that of Example 1 (Figure 1a). Its elevation is similar to that of Example 1 with the same uniform story height of 3.66 m (12 ft) but total height of 219.4 m (720 ft) giving the structure an aspect ratio of 7.2. The members are divided into 300 groups of members. A W shape is selected for each group. The groups are organized similar to Examples 1 and 2. The loadings on the structure, the material properties and the lower and upper bounds of the cross-sectional areas are the same as those of Example 1. The displacement constraints are given as ± 87.78 cm (34.56 in.) in the X-direction for nodes on the top level (equal to 0.004*H*) Figure 4 shows the convergence history. A minimum weight of 61.6 MN (13,862 kips) is found after 8 iterations. This translates into 1.11 kPa (23.10 lbs/ft^2) when the weight is divided by the total floor area provided by the structure

PERFORMANCE EVALUATION

The performance of the parallel-vector optimization algorithm is evaluated in this section in terms of speedup and MFLOPS on Cray YMP8/864 supercomputer with eight processors. The computation time is dominated by three steps: evaluation and assembly of stiffness matrices, solution of the resulting linear equations for nodal displacements, and calculation of the displacement gradients. Therefore, speedup curves are presented for these steps as well as the complete optimization process.

Performance results in terms of millions of floating operations per second (MFLOPS) and speedup are summarized in Table 1. The MFLOPS numbers in this table are for a processor only and represent the vectorization efficiency of the algorithm. Figures 5 to 7 present the speedup results for Examples 1 to 3 respectively, due to parallel processing (relative to the vectorized code running on one processor only). Figure 8 shows the speed due to both vectorization and parallel processing for the four examples.

One clear trend can be observed in Figures 5 to 8 and Table 1: parallelization efficiency improves with the increase in the size of the structures. The same trend is observed for speedup due to vectorization but to a smaller extent. For the largest structure we achieved a speedup of 6.4 due to parallel processing (using eight processors) only and a speedup of

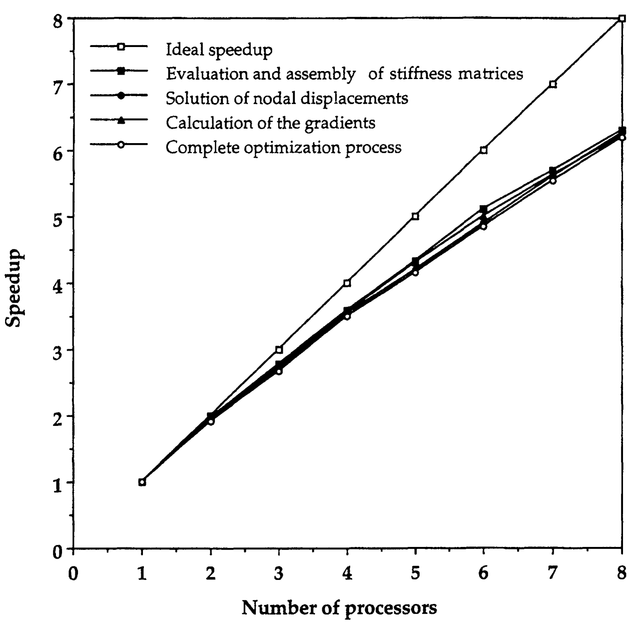

Fig. 6. Speedups due to parallel processing only for Example 2.

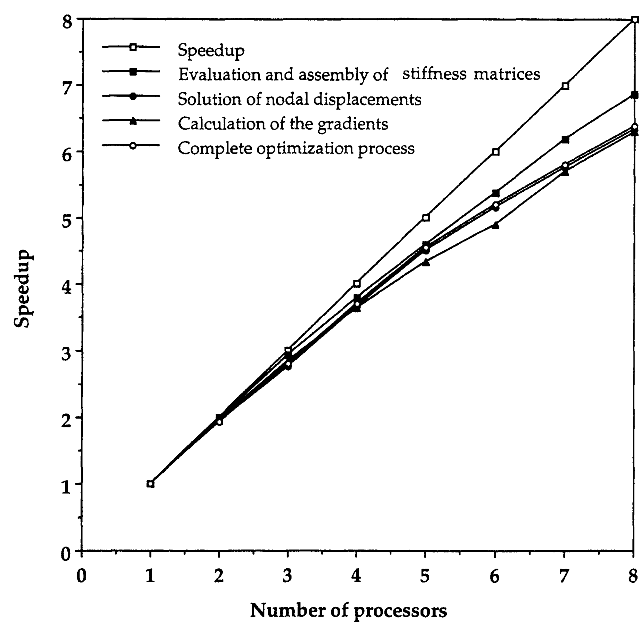

Fig. 7. Speedups due to parallel processing only for Example 3.

17.8 due to vectorization only. When vectorization is combined with parallel processing a combined speedup of 97.1 is achieved. Note that this number is somewhat smaller than the product of the previous two numbers ($6.4 \times 17.8 = 113.9$) because parallel processing degrades vectorization. Judicious integration of parallel processing and vectorization is necessary to avoid substantial degradation in vectorization. This is particularly important in light of the fact that speedup due to vectorization is substantially more than speedup due to parallel processing for a shared memory machine with a few processors.

CONCLUDING

We are living in an increasingly automated society. This innovative research demonstrates how design of large steel structures with thousands of members can be automated. The economic consequences of such large scale automation in terms of both reducing the time of design and cost of the structure are enormous. The work presented in this paper was done on a supercomputer with multiprocessing capability. It is only a matter of time that practicing engineers will find such computing capability on their desktops. Today, it takes months to design a superhighrise building structure. This research lays the foundation to reduce that time to only a few days.

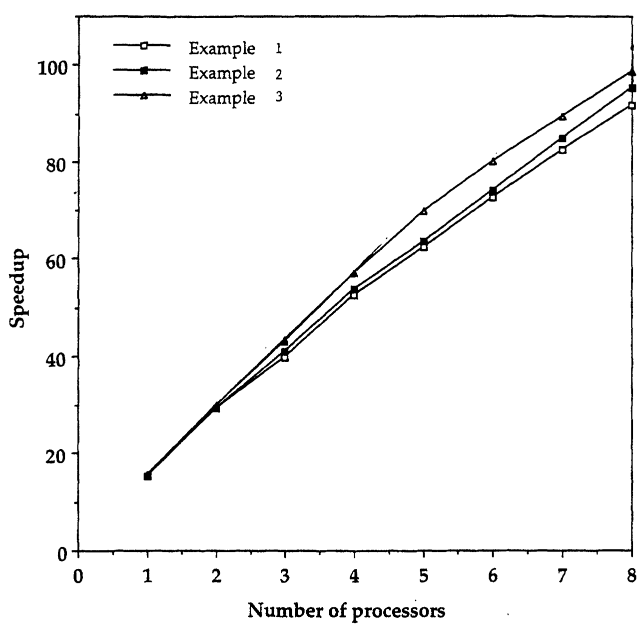

Fig. 8. Overall speedups due to parallel processing and vectorization for Examples 1 to 3.

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