Structural Optimization with Tabu Search

Mohsen Kargahi[1]
James C. Anderson[2]
Maged M. Dessouky[3]

Abstract:

A class of search techniques for discrete optimization problems, Heuristic Search Methods, and their suitability for structural optimization are studied. The Tabu Search method is selected for application to structural weight optimization of skeleton structures. The search method is first tested to find the minima of a function in a non-linear non-convex optimization mathematical problem, and an algorithm is developed. Further, a computer program is developed that uses Tabu Search for weight minimization of two-dimensional framed structures. The program, written in the FORTRAN computer language, performs search, structural analysis, and structural design in an iterative procedure. The program is used to optimize the weight of three previously designed frames including 3-story/3-bay, 9-story/5-bay, and 20-story/5-bay steel moment resisting frames. The program demonstrated its capability of optimizing the weight of these medium size frames in a reasonable amount of time without requiring engineer interface during the search. The structural weights for the three frames are reduced by an average of 23.4% from their original design weight.

Introduction:

Structural design has always been a very interesting and creative segment in a large variety of engineering projects. Structures, of course, should be designed such that they can resist applied forces (stress constraints), and do not exceed certain deformations (displacement constraints).

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[1]Senior Engineer, Weidlinger Associates, Inc., 2525 Michigan Avenue, #D2-3, Santa Monica, California, 90404

[2] Professor, Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, California, 90089

[3] Associate Professor, Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, California, 90089

Moreover, structures should be economical. Theoretically, the best design is the one that satisfies the stress and displacement constraints, and results in the least cost of construction. Although there are many factors that may affect the construction cost, the first and most obvious one is the amount of material used to build the structure. Therefore, minimizing the weight of the structure is usually the goal of structural optimization.

The main approach in structural optimization is the use of applicable methods of mathematical programming. Some of these are Linear Programming (LP), Non-Linear Programming (NLP), Integer Linear Programming (ILP), and Discrete Non-Linear Programming (DNLP).

When all or part of the design variables are limited to sets of design values, the problem solution will use discrete (linear or non-linear) programming, which is of great importance in structural optimization. In fact, when the design variables are functions of the cross sections of the members, which is the case for most structural optimization problems, they are often chosen from a limited set of available sections. For instance, steel structural elements are chosen from standard steel profiles (e.g., WF, etc.), structural timber is provided in certain sizes (e.g., 4x8, etc.), concrete structural elements are usually designed and constructed with discrete dimensional increments (e.g., 1 inch, or ½ inch), and masonry buildings are built with standard size blocks (e.g., 8", or 10").

Another important issue to point out is that the nature of structural optimization problems is usually non-linear and non-convex. Therefore algorithms for mathematical programming may converge to local optima instead of a global one.

Finally, there has always been the method of Total Enumeration for discrete optimization problems. In this method, all possible combinations of the discrete values for the design variables are substituted, and the one resulting in the minimum value for the objective function, while satisfying the constraints, is chosen. This method always finds the global minimum but is slow and impractical. However, some newly developed techniques, known as heuristic methods, provide means of finding near optimal solutions with a reasonable number of iterations. Included in this group are Simulated Annealing, Genetic Algorithms, and Tabu Search. Moreover, the reduction in computation cost in recent years, due to the availability of faster and cheaper computers, makes it feasible to perform more computations for a better result.

As far back as the 19th century, Maxwell (1890) established some theorems related to rational design of structures, which were further generalized by Michell (1904). In the 1940's and 1950's, for the first time, some practical work in the area of structural optimization was done (Gerard, 1956; Livesley 1956; Shanley, 1960). Schmit (1960) applied non-linear programming to structural design. By the early 1970's, with the development of digital computers, which provided the capability of solving large scale problems, the field of structural optimization entered a new era and since then numerous research studies have been conducted in this area. Wu (1986) used the Branch-and-Bound method for the purpose of structural optimization. Goldberg and Samtani (1986) performed engineering optimization for a ten member plane truss via Genetic Algorithms. The Simulated Annealing algorithm was applied to discrete optimization of a three-dimensional six-story steel frame by Balling (1991). Jenkins (1992) performed a plane frame optimization design based on the Genetic Algorithm. Farkas and Jarmai (1997) described the Backtrack discrete mathematical programming method and gave examples of stiffened plates, welded box beams, etc. R. J. Balling (1997), in the AISC "Guide to Structural Optimization", presents two deterministic combinatorial search algorithms, the exhaustive search algorithm and the Branch-and-Bound algorithm.

Scope of This Study:

Advances in the speed of computing machines have provided faster tools for long and repetitive calculations. Perhaps, in the near future, an ideal structural analysis and design software program will be able to find the near optimal structure without any given pre-defined properties of its elements.

A structural optimization approach is proposed which is appropriate for the minimum weight design of skeleton structures, e.g., trusses and frames. Taking advantage of the Tabu Search algorithm, structural analysis and design are performed repetitively to reach an optimal design.

A computer program that is capable of finding the best economical framed structure satisfying the given constraints, in a structural optimization formulation based on Tabu search, is developed and evaluated. The program performs search, analysis and design operations in an iterative manner to reduce the structural weight while satisfying the constraints.

Several frame structures are optimized using the program. For each problem, the program is fine-tuned by varying the two main search parameters, tabu tenure and frequency penalty, in order to achieve the least weight.

Tabu Search for Combinatorial Problems:

The distinguishing feature of Tabu search relative to the other two heuristic methods, genetic algorithm and simulated annealing, is the way it escapes the local minima. The first two methods depend on random numbers to go from one local minimum to another. Tabu Search, unlike the other two, uses history (memory) for such moves, and therefore is a learning process. The modern form of Tabu Search derives from Glover and Laguna (1993). The basic idea of Tabu Search is to cross boundaries of feasibility or local optimality by imposing and releasing constraints to explore otherwise forbidden regions. Tabu Search exploits some principles of intelligent problem solving. It uses memory and takes advantage of history to create its search structure.

Tabu Search begins in the same way as ordinary local or neighborhood search, proceeding iteratively from one solution to another until a satisfactory solution is obtained. Going from one solution to another is called a move. Tabu search starts similar to the steepest descent method. Such a method only permits moves to neighbor solutions that improve the current objective function value. A description of the various steps of the steepest descent method is as follows.

1. Choose a feasible solution (one that satisfies all constraints) to start the process. This solution is the present best solution.

2. Scan the entire neighborhood of the current solution in search of the best feasible solution (one with the most desirable value of objective function).

3. If no such solution can be found, the current solution is the local optimum, and the method stops. Otherwise, replace the best solution with the new one, and go to step 2.

The evident shortcoming of the steepest descent method is that the final solution is a local optimum and might not be the global one.

Use of memory is the tool to overcome this shortcoming in Tabu Search. The effect of memory may be reviewed as modifying the neighborhood of the current solution (Glover and Laguna 1997). The modified neighborhood is the result of maintaining a selective history of the states encountered during the search.

Recency-based memory is a type of short-term memory that keeps track of solution attributes that have changed during the recent past. To exploit this memory, selected attributes that occur in solutions recently visited are labeled tabu-active, and solutions that contain tabu-active elements are those that become tabu. This prevents certain solutions from the recent past from belonging to the modified neighborhood. Those elements remain tabu-active for a number of moves called the tabu tenure.

Frequency-based memory is a type of long-term memory that provides information that complements the information provided by recency-based memory. Basically, frequency is measured by the counts of the number of occurrences of a particular event. The implementation of this type of memory is by assigning a frequency penalty to previously chosen moves. This penalty would affect the move value of that particular move in future iterations.

A description of the various steps of the Tabu Search method is as follows.

1. Choose a feasible solution to start the process. This solution is the present best solution.

2. Scan the entire neighborhood of the current solution in search of the best feasible solution.

3. Replace the best solution with the new one. Update the recency-based and frequency-based memories and go to step 2.

Before approaching the structural optimization problem the algorithm is applied to a simple, discrete, two-variable, non-convex minimization problem as shown in Figure 1. The search was performed with frequency penalty of 1 and tabu tenure of 3. Candidates outside the feasible region are subject to a penalty. A penalty of 1000 is added to the move values falling outside the feasible region to impose this constraint. The algorithm found the two minima by making 21 moves (from node 1 to 22), as shown in Figure 1.

Mathematical Problem Formulation:

The general weight-based structural optimization problem for skeleton structures with "n" members and "m" total degrees of freedom can be stated as:

Minimize	$Z=\sum A_i L_i$	$i = 1,2,\ldots,n$
Subject to:	$D_j \leq D_{jmax}$	$j = 1,2,\ldots,m$
	$-S_{imin} \leq S_i \leq S_{imax}$	

Where A_i's are the cross sectional areas of the members (design variables), L_i's are the lengths of the members, D_j's are the nodal displacements, and S_i's are the stresses in the members. Unlike the conventional way of stating a mathematical programming problem, the constraints in the above problem do not contain the design variables, A_i's.

It can be seen that the objective function Z, is a linear function of the design variables (A_i's). Unfortunately this is not the case for the constraint functions. The constraints are non-linear functions of the design variables. In order to show this we should briefly discuss the displacement (stiffness) method, the most common method for structural analysis. This method is based on the basic equation of KD=R, where K is the m×m global stiffness matrix of the structure (where the coefficients k_{ij}'s are defined as the force at node i due to a unit displacement at node j), D is the m×1 vector of global joint displacements, and R is the m×1 vector of global applied nodal forces.

The solution to this problem is obtained by matrix algebra by multiplying both sides of the equation by K^{-1} resulting in equations of the form $D=K^{-1}R$. In order to examine the components of the matrix K^{-1}, look at the components of matrix K, considering the simple case of a truss problem. Each component of the stiffness matrix of a truss consists of the summation of the elements in the form of E_iA_i/L_i, which is a linear function of the design variables. However, in the process of inversion of matrix K, the A_i elements will appear in the denominator of matrix K^{-1}, and will make the elements of the inverse matrix non-linear functions of the A_i's. This in turn makes the elements of vector D, obtained by the product of $K^{-1}R$, non-linear functions of the A_i's. Similar reasoning can be used for flexural elements. For beam problems, the elements of the stiffness matrix K consist of E_iI_i/L_i terms and therefore I_i terms will appear in the denominator of the K^{-1} matrix elements. For a general frame problem both $\sum c_iA_i$ and $\sum c_iI_i$ (with c_i's being constants) terms will appear in the numerator of the K matrix elements, and therefore in the denominator of the K^{-1} matrix elements.

As the problem indicates, the constraints consist of restrictions on the stresses and displacements. Since the subject of the study is the optimization of steel structural frames, the AISC-ASD Specifications for Structural Steel Buildings (1989) is chosen for the purpose of determining the constraints on the stresses. For beams, the allowable flexural stress is calculated using the given formulas and compared to the demand in the beam members. For columns, the combined axial/flexural stress check as outlined in the specification is performed. The AISC specification does not provide limiting values for displacements or inter-story drifts. Those values are obtained from the building code used for the design of the case study buildings (1994 UBC).

Tabu Search and Structural Optimization:

It is competitively prohibitive to find the optimal solution of the above structural optimization problem. However, Tabu Search can be used to find a near-optimal solution. In such a problem, the design variables are the cross sections for the structural elements and are chosen from a set (or sets) of available sections sorted by their weight per unit length (or cross sectional area). The objective function to be minimized is the weight of the structure that is calculated by summing the product of weight per unit length by length for all structural elements.

A move then consists of changing the cross section of an element to one size larger or one size smaller. Therefore, for a frame with n structural elements there will be 2xn moves at anytime during the search. The constraints are the stresses in the structural elements and the inter-story drifts for all story levels. The considered stresses are bending, combined axial and bending, and shear stresses.

The starting point of the search must be a structural configuration that satisfies the stress and displacement constraints. The search begins by evaluating the frame weight at the entire neighborhood of the starting point and the corresponding move values, choosing the best move (the one that results in the most weight reduction). The required replacements are then made to the structural properties, and structural analysis is performed. Based on the analysis results, stress and displacement constraints are checked. If all of the constraints are satisfied, the move is feasible and the search algorithm has found a new node. If any of the constraints are not satisfied, the structural configuration is set back to its original form, the second best move is selected, the corresponding changes are made to the structural model, and the analysis and constraint evaluation processes are repeated. This procedure is continued until a move that satisfies all the constraints is found. The search algorithm is now at a new node. At this stage, the tabu tenure and frequency penalty for the performed move are applied to the selected move and the program proceeds by repeating the same algorithm at the new node.

It should be noted that a move is not finalized unless all constraints for the structural configuration that is the result of that move are satisfied. Therefore, there is no chance of staying in the infeasible region. For instance if a move results in a structural configuration with drift ratios exceeding the required limits, it will not be an acceptable move. Instead, the algorithm will go back to the previous configuration and take the next best move.

The tabu tenure is applied by prohibiting the reverse of a move for a certain duration (e.g. if the section for element “i” is reduced to a smaller section, changing it back to the larger section becomes prohibited for a duration of tabu tenure, and vice versa). The frequency penalty is applied in the form of a positive number added to the move value of a particular move (good moves have negative move values) and therefore reducing its chance for being selected as the best move in the future (e.g. if the section for element “i” is reduced to a smaller section, the move value of reducing the section of element “i” in the future will contain the frequency penalty).

Tabu Search Optimization Computer Program:

A structural optimization program is developed in the FORTRAN computer language using Tabu Search as a means of finding the near minimum weight for a framed structure under given static load conditions.

The main body of the program is the implementation of the Tabu Search method, as described earlier. This part of the program keeps track of the moves based on their recency and frequency, chooses the neighboring candidates at each stage, and prepares the required data for the next stages. This set of data contains cross-sectional properties for all elements of the structure.

The program also contains the necessary structural analysis subroutines. Direct stiffness method is used for this purpose. The output of this part is nodal displacements and internal member forces, which are the inputs necessary for the next part.

Finally, the constraint evaluation part of the program contains a stress check subroutine based on AISC-ASD Specification (1989), and a story drift check subroutine based on building code requirements.

The search method also requires accessing section properties for a given set of available sections. The section properties are listed in section property data files. Since beams and columns are usually selected from different types of W-sections, two different section property files are generated, one for beams and the other for columns. Also, a third data file is prepared for the elements that are not part of the search. These are referred to as non-iterating elements and their size does not change during iterations.

A grouping method is implemented in the program by simply putting the elements that are desired to have the same section in one group and treating the group as one independent variable. In addition to resulting in more practical designs, the number of independent variables and therefore the time to run the program is reduced. The search method changes sections for the entire group of elements instead of a single structural element.

Strong Column/Weak Beam requirements based on the AISC Seismic Provisions for Structural Steel Buildings (1997) are added to the program to further increase the practicality of the final designs.

Case Studies:

After completion initial tests, the program is used to optimize three two-dimensional moment resisting frames. All three frames are representative of existing steel structures in the Los Angeles area and were part of a SAC program of study following the Northridge earthquake (Mercado et al, 1997). The structures and their typical plans are shown in Figure 2 and will be called the 3-story, 9-story, and 20-story SAC frames (or SAC-3, SAC-9, and SAC-20) in this work. The structural information, including the pre-Northridge design element sections which were taken as the starting point for the Tabu Search, are extracted from the same report. It should be noted that the starting point is a possible feasible solution.

Grouping is used to reduce the number of design variables and to maintain consistency with the original frames. The beam elements for each story level form a beam group, and the column groups are chosen according to the column splice location taken from the original drawings. Generally, external and internal columns of each two or three stories are grouped together. As a result SAC-3 has 2 column groups and 3 beam groups; SAC-9 has 10 column groups, 10 beam groups, and 5 non-iterating column groups (these columns are part of the moment frame in the perpendicular direction and not the direction under study); and SAC-20 has 16 column groups and 22 beam groups. The search is fine-tuned by changing the values of the Tabu Search parameters, tabu tenure and frequency penalty, to obtain better results.

The distributed gravity loads on beams and gravity point loads on columns due to reaction from beams in the perpendicular direction are extracted form the existing reports and applied to the frames. The earthquake loads are calculated and distributed based on the lateral force provisions of the 1994 UBC (method A) according to the formula for base shear, $V=(ZIC/R_w)W$, while the structural period calculated using method B is used for drift considerations. Simple models built in SAP2000 resulted in fundamental periods exceeding 0.7 seconds for all three frames. Therefore, the limiting drift ratio given as the minimum of $0.03/R_w$ and 0.004, is calculated to be 0.0025 using $R_w=12$. Using method B to calculate the fundamental periods permits reduction in the lateral loads for drift calculations by ratios of 0.6224, 0.6394, and 0.6646 for SAC3, SAC9, and SAC20 respectively. For stress check purposes three load combinations are considered, gravity, 0.75x(gravity+seismic), and 0.75x(gravity-seismic). For calculating the drift, the seismic forces are reduced by the above factors and applied in both directions. The original designs of the 9-story and 20-story frames were mainly displacement controlled, while the initial design of the 3-story frame was mainly force controlled.

First, the **3-story**, 3-bay (originally 4-bay including a non-moment-frame bay) Special Moment Resisting Frame (SMRF), shown in Figure 3, is considered for optimization using the computer program. The starting point used the sections from the original design with a total weight of 32,056 kg (70,764 lb). To study the effects of search parameters on the achieved minimum weight, the search is performed with 6 different tabu tenures and 7 different frequency penalties for 100 iterations. The chosen tabu tenures are 3, 4, 5, 6, 7, and 8; and the chosen frequency penalties are 9, 10, 11, 12, 13, 14, and 15 per element in each element group.

Figure 4 illustrates the variation of achieved minimum weight with tabu tenure for different values of frequency penalty for 100 iterations. All frequency penalties are able to reach the same minimum weight. Figure 5 illustrates the variation of achieved minimum weight with frequency penalty for different values of tabu tenure for 100 iterations. All tabu tenures except tabu tenure of 7 result in the same minimum weight. The variation of frame weight in 100 iterations for tabu tenure of 5 and frequency penalty of 11 is shown in Figure 6. The achieved minimum weight is 23,579 kg (50,748 lb), illustrating a weight reduction of 26.4%. Figure 7 illustrates average final stress ratios for columns and beams at all story levels. The overall average column and beam stress ratios are 0.595 and 0.715 respectively. The inter-story drift ratios are also shown in Figure 7. The overall average drift ratio is 0.00215. The stress ratios in the columns of upper two stories are relatively low due to the constraint of keeping column size constant. Considering this and the relative low value of the drift ratios, it can be concluded that the design of the 3-story frame is mostly force controlled.

Second, the **9-story** (10-story including the laterally supported first floor), 5-bay (one of the bays has moment connection on one side only) SMRF frame (Figure 8) is considered for optimization using the developed program. The starting point was intended to be the sections from the original design of the structure. However, the beam sections of the 6th and 7th floors are changed in order to make the structure compliant with the Strong Column Weak Beam (SC/WB) requirements. The original beam section of W36x135 is changed to W33x130 and W33x118 for the 6th and 7th floors respectively. Total weight at the starting point is 194,848 kg (430,128 lb). To study the effects of tabu tenure and frequency penalty on the search performance, the search is initially performed with 6 different tabu tenures and 7 different frequency penalties, for 100 iterations (42 runs). The chosen tabu tenures are 3, 4, 5, 6, 7, and 8; and the chosen frequency penalties are 9, 10, 11, 12, 13, 14, and 15 per element in each element group.

The variation of achieved minimum weight with tabu tenure for different values of frequency penalty for 100 iterations is illustrated in Figure 9. Frequency penalties of 13 and 14 result in the minimum achievable weight. Figure 10 illustrates the variation of achieved minimum weight with frequency penalty for different values of tabu tenure for 100 iterations. Tabu tenure of 8 results in the minimum weight of 160,568 kg (354,454 lb) showing a weight reduction of 17.6%. Since the minimum values are obtained at the very last iteration step, a new series of searches are performed for 200 iterations. Also since the largest tabu tenure (8) results in the best value, tabu tenures larger than 8 are included for the next stage. At this stage, tabu tenures of 7, 8, 9, and 10, and frequency penalties of 13, and 14 are considered. A search with tabu tenure of 9 and frequency penalty of 13 or 14 results in a minimum weight of 159,211 kg (351,460 lb) at iteration 195 showing a weight reduction of 18.3% from the starting point. The variation of frame weight in 200 iterations for tabu tenure of 9 and frequency penalty of 13 is shown in Figure 11. Figure 12 illustrates average final stress ratios for columns and beams at all story levels. The overall average column and beam stress ratios are 0.492 and 0.704 respectively. The inter-story drift ratios are also shown in Figure 12. The overall average drift ratio is 0.00239.

Since there are low stress ratios in the columns while all drift ratios are very close to the limiting value of 0.0025, it can be concluded that the design of the 9-story frame was entirely displacement controlled.

Finally, the **20-story** (22-story including the laterally supported basement and sub-basement), 5-bay SMRF frame (Figure 13) is considered for optimization using the developed computer program. The starting point was intended to be the sections from the previous design of the frame. However, the interior column sections of the 21st and 22nd story levels are changed in order to make the structure compliant with the Strong Column Weak Beam (SC/WB) requirements. The original column section of W24x94 is changed to W24x104. Total weight at the starting point is 271,060 kg (598,366 lb). In order to study the effects of tabu tenure and frequency penalty on the search performance, the search is initially performed with 6 different tabu tenures and 7 different frequency penalties, for 100 iterations (42 runs). The chosen tabu tenures are 4, 5, 6, 7, 8, and 9; and the chosen frequency penalties are 10, 11, 12, 13, 14, 15, and 16 per element in each element group.

Figure 14 illustrates the variation of achieved minimum weight with tabu tenure for different values of frequency penalty for 100 iterations. Frequency penalties 11, 12, 13, 14, and 15 are able to find a minimum weight that is less than the minimum weight with frequency penalties of 10 and 16. Figure 15 illustrates the variation of achieved minimum weight with frequency penalty for different values of tabu tenure for 100 iterations. Tabu tenures 4, 5, 6, and 8 result in a minimum weight less than the minimum weight from tabu tenures 7 and 9. This minimum weight is 210,872 kg (465,500 lb) showing a weight reduction of 22.2%. Considering the large number of structural elements that demands more iteration steps for a thorough search, and the fact that most minimum values are obtained at the very last iteration step, further search with a larger number of iterations is performed. The second series of searches is done for 200 iterations. At this stage, tabu tenures of 4, 5, 6, 7, and 8, and frequency penalties of 11, 12, 13, 14, and 15 are considered. The achieved minimum weight is 209,712 kg (462,940 lb) corresponding to a weight reduction of 22.6%. Comparison of weight reductions shows no significant improvement by increasing the number of iterations to 200. However, for the reasons stated before the potential for more weight reduction still exists.

The third series of searches is performed for 300 iterations. At this stage, tabu tenures of 5, 6, and 7, and frequency penalties of 11, 12, and 13, which resulted in lower weights during previous search, are considered. The achieved minimum weight is 204,457 kg (451,340 lb) corresponding to a weight reduction of 24.6%. The program is able to reach a considerably lower weight by going to 300 iterations from 200 iterations. Finally, the fourth series of searches are performed for 400 iterations. At this stage, tabu tenures of 5, 6, and 7, and frequency penalty of 13, which resulted in lower weights during previous searches, are considered. The achieved minimum weight is 201,807 kg (445,490 lb) showing a weight reduction of 25.5%. The variation of frame weight in 400 iterations for the best achieved weight having tabu tenure of 7 and frequency penalty of 13 is shown in Figure 16. Figure 17 illustrates average final stress ratios for columns and beams at all story levels. The overall average column and beam stress ratios are 0.646 and 0.691 respectively. The inter-story drift ratios are also shown in Figure 17. The overall average drift ratio is 0.00239. With the exception of the lower level elements, stress ratios are not high while all drift ratios are very close to the limiting value of 0.0025. Therefore, it can be concluded that the design of the 20-story frame is largely displacement controlled, particularly in the upper story levels.

Summary and Conclusions:

As an alternative/automated approach to the analysis and design of framed steel structures, an optimization based structural analysis and design program is developed. The algorithm performs search, structural analysis, and structural design iteratively, using Tabu Search method.

The developed Tabu Search structural optimization program proves capable of achieving considerable weight reduction for two-dimensional frames. Medium size frames are analyzed and designed in a reasonable time, while engineer interface during the search is not required. To improve efficiency of the method, several searches are performed with different search parameters and the duration of search is increased if needed. The program is utilized to reduce the structural weights for the three case study structures, a 3-story,3-bay, a 9-story,5-bay, and a 20-story,5-bay frame, resulting in 26.4%, 18.3%, and 25.5% weight reductions respectively. Similar to the original designs, the final Tabu Search designs of the 9-story and 20-story frames are displacement controlled, whereas the final design of the 3-story frame is mostly force controlled.

The 3 frames under study are analyzed and designed using a personal computer with an Intel Pentium II, 233 MHz processor that is relatively slow by current standards. The program is able to achieve significant weight reductions in a reasonable time. Table 1 contains frame information and a sample run time for the analyzed frames.

The seismic performance of the Tabu Search designed frames will be evaluated and compared with that of the original frames in a companion paper.

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Minimize f=2X1+3X2
Subject to the constraint shown
X1,X2 from {1,2,3,4,5,6,7,8,9,10}

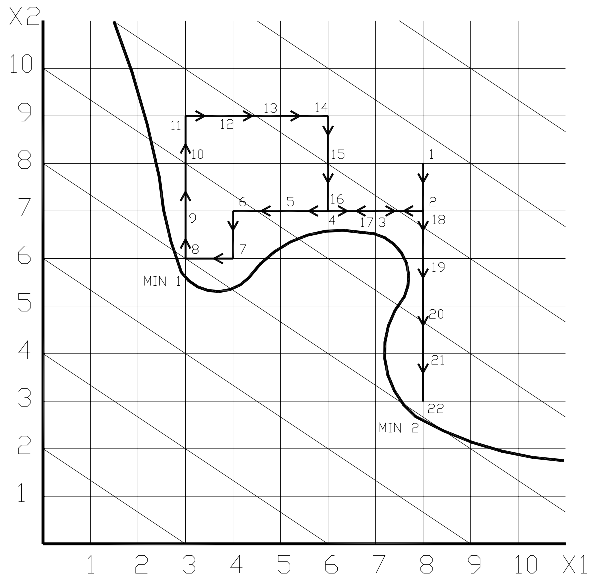

Figure 1. Finding the two minima of a function, tabu tenure = 3, frequency penalty=1

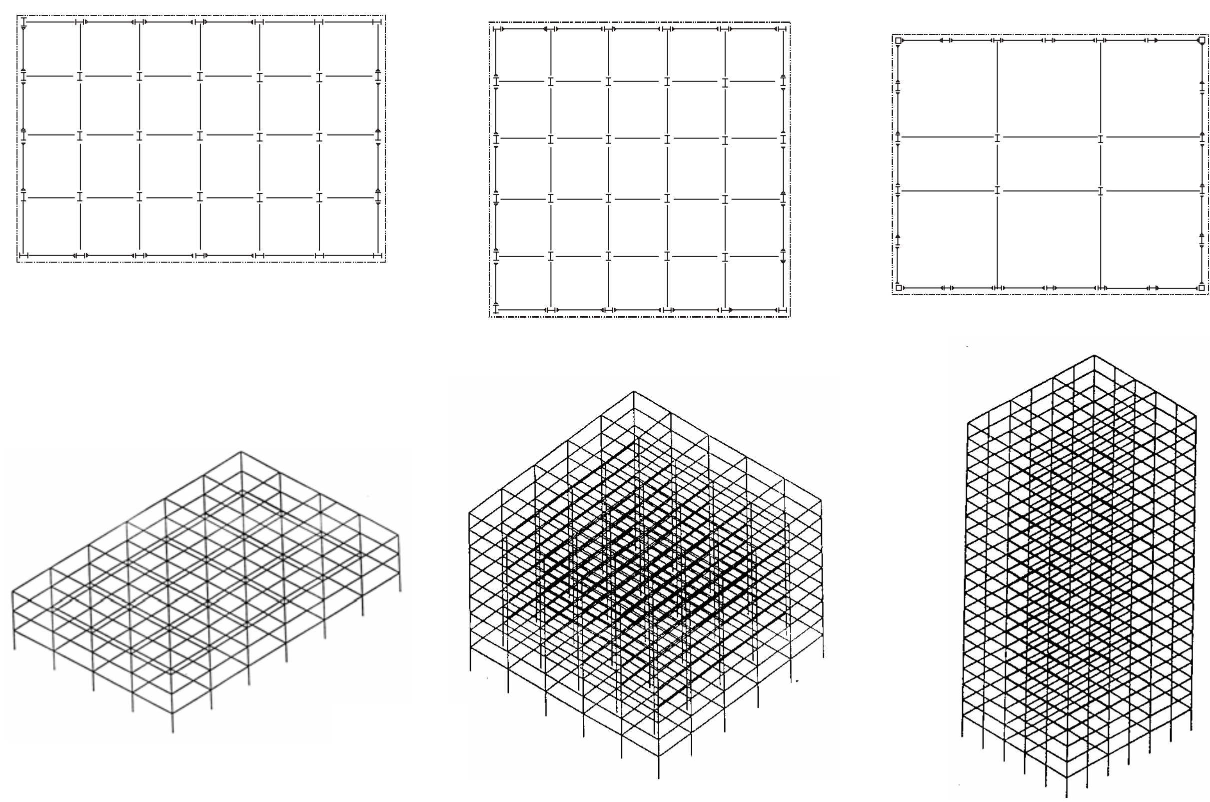

Figure 2. Structural framing and typical floor plans for the three SAC buildings

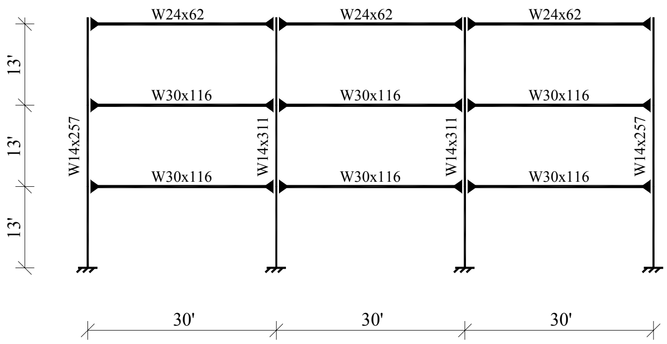

Figure 3. 3-story SAC – Original frame

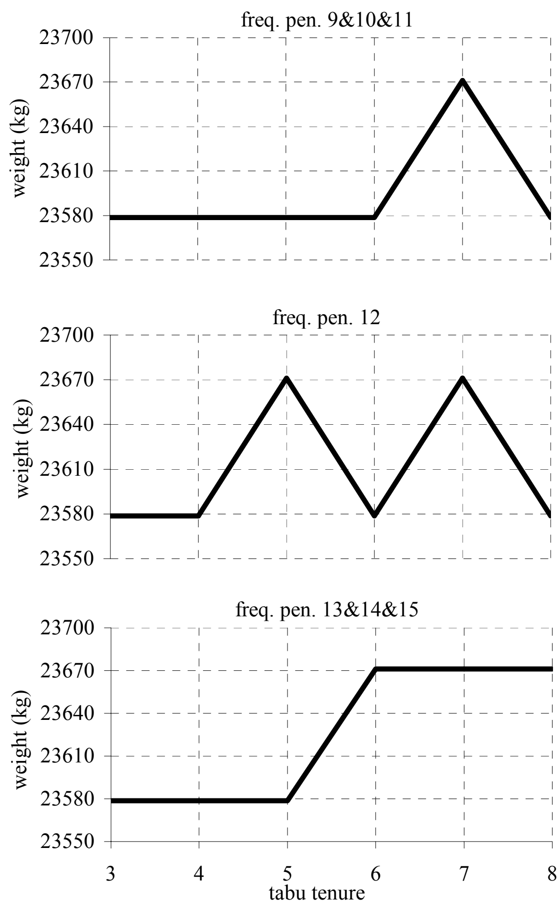

Figure 4. 3-story SAC - Variation of achieved minimum weight with tabu tenure for different frequency penalties

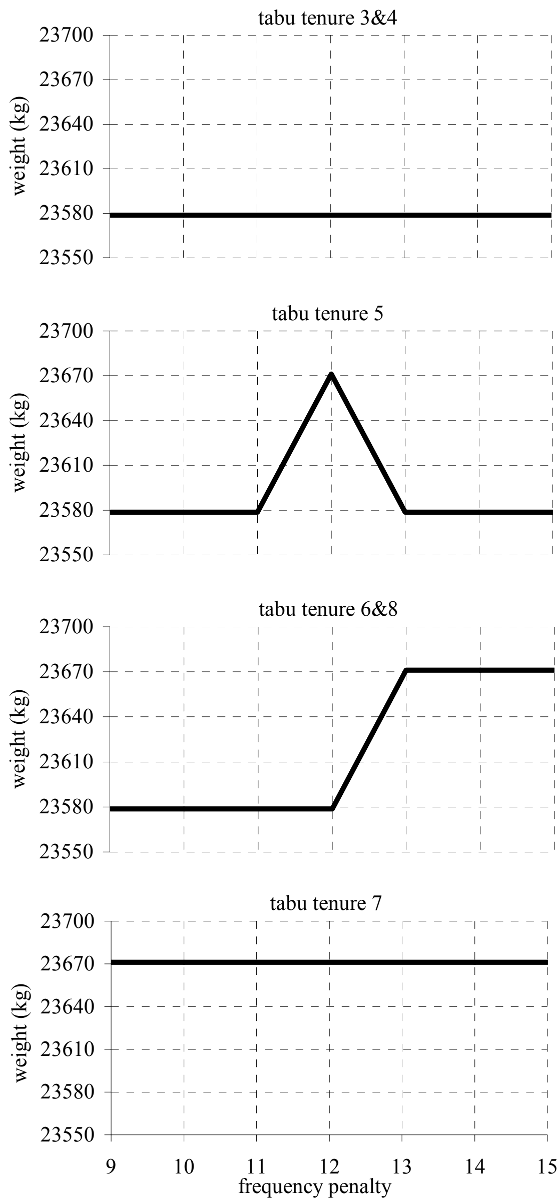

Figure 5. 3-story SAC - Variation of achieved minimum weight with frequency penalty for different tabu tenures

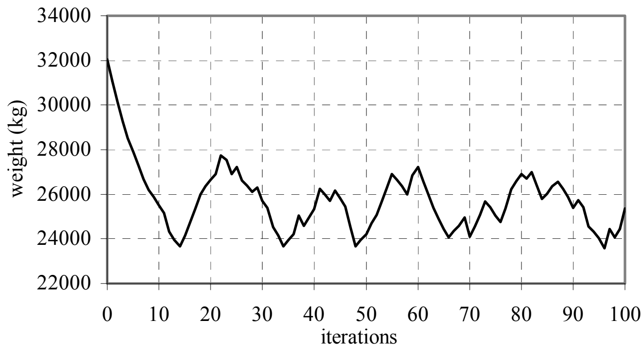

Figure 6. 3-story SAC - Variation of weight with iterations for tabu tenure of 5 and frequency penalty of 11

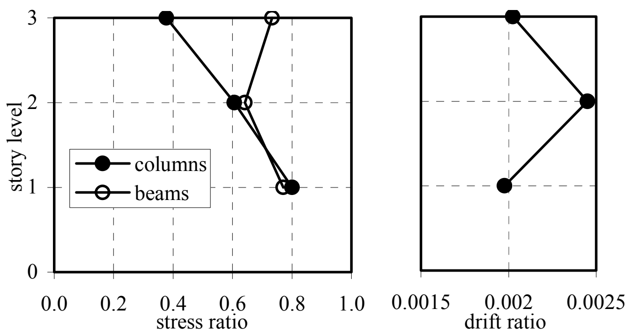

Figure 7. 3-story SAC – Final stress and drift ratios

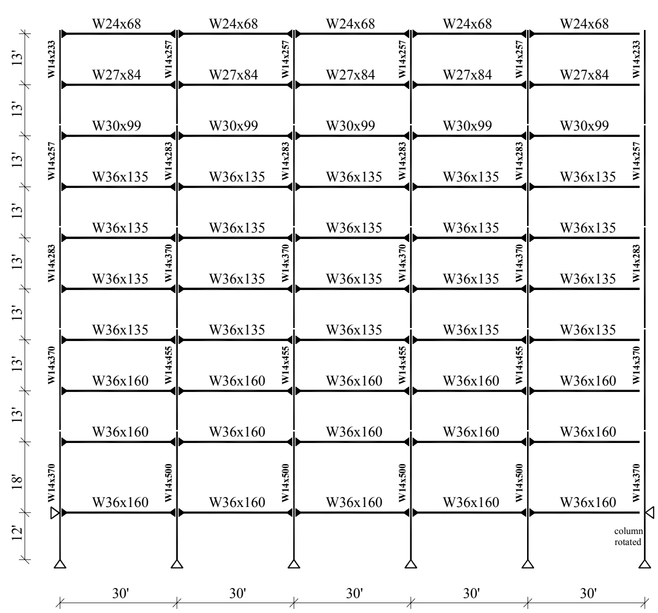

Figure 8. 9-story SAC – Original frame

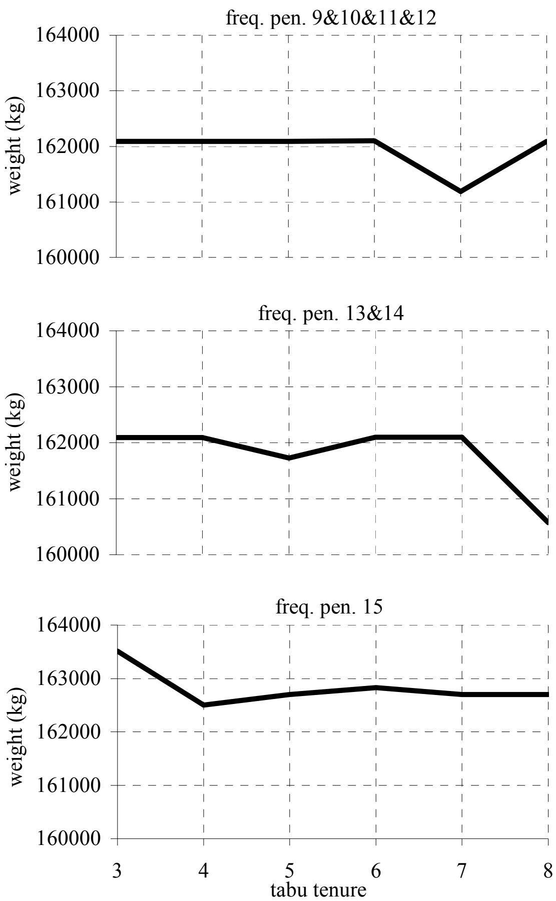

Figure 9. 9-story SAC - Variation of achieved minimum weight with tabu tenure for different frequency penalties, 100 iterations

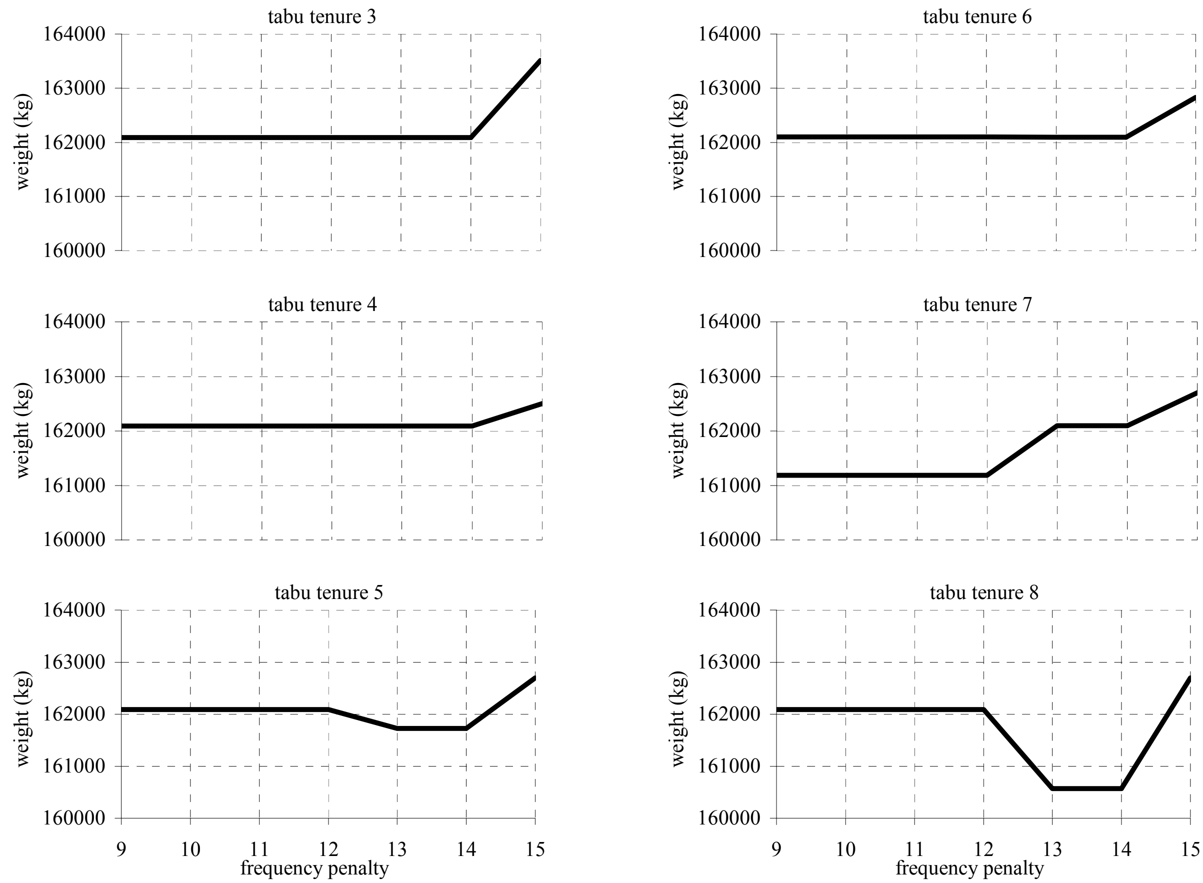

Figure 10. 9-story SAC - Variation of achieved minimum weight with frequency penalty for different tabu tenures, 100 iterations

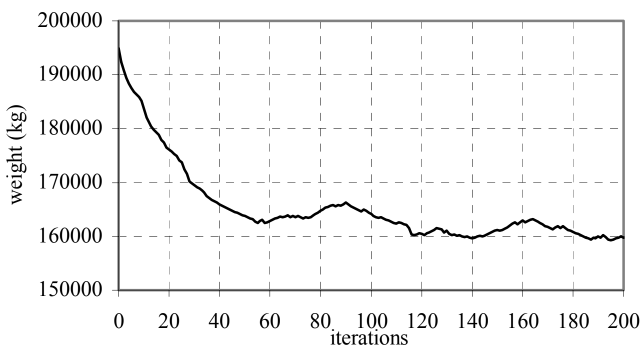

Figure 11. 9-story SAC - Variation of weight with iteration for tabu tenure of 9 and frequency penalty of 13, 200 iterations

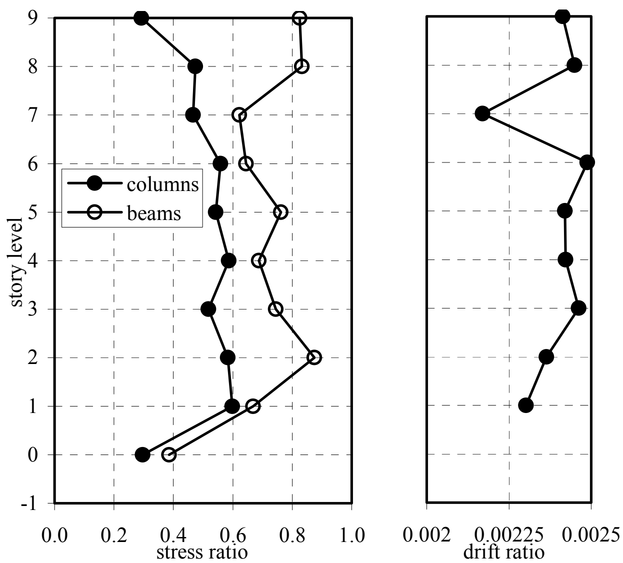

Figure 12. 9-story SAC – Final stress and drift ratios

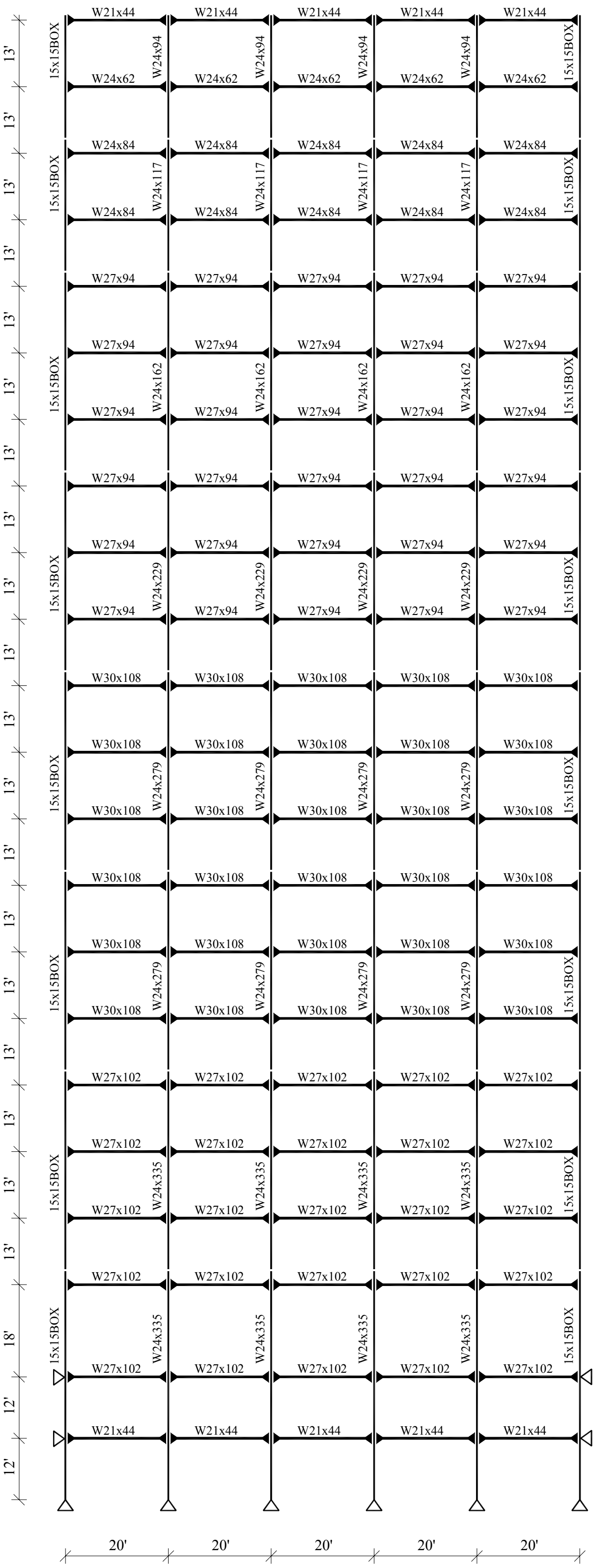

Figure 13. 20-story SAC – Original frame

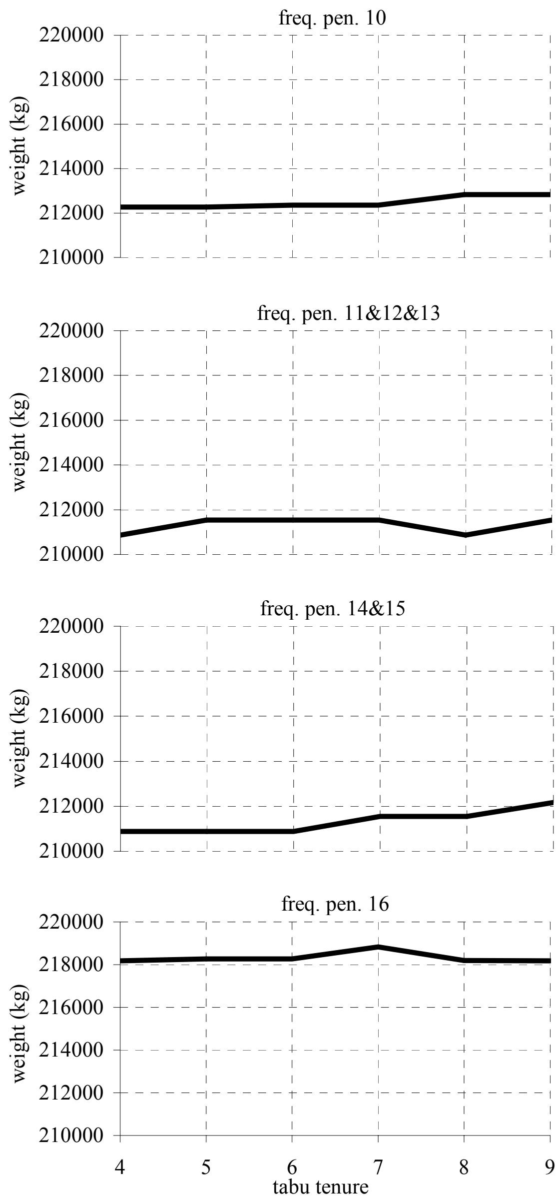

Figure 14. 20-story SAC - Variation of achieved minimum weight with tabu tenure for different frequency penalties, 100 iterations

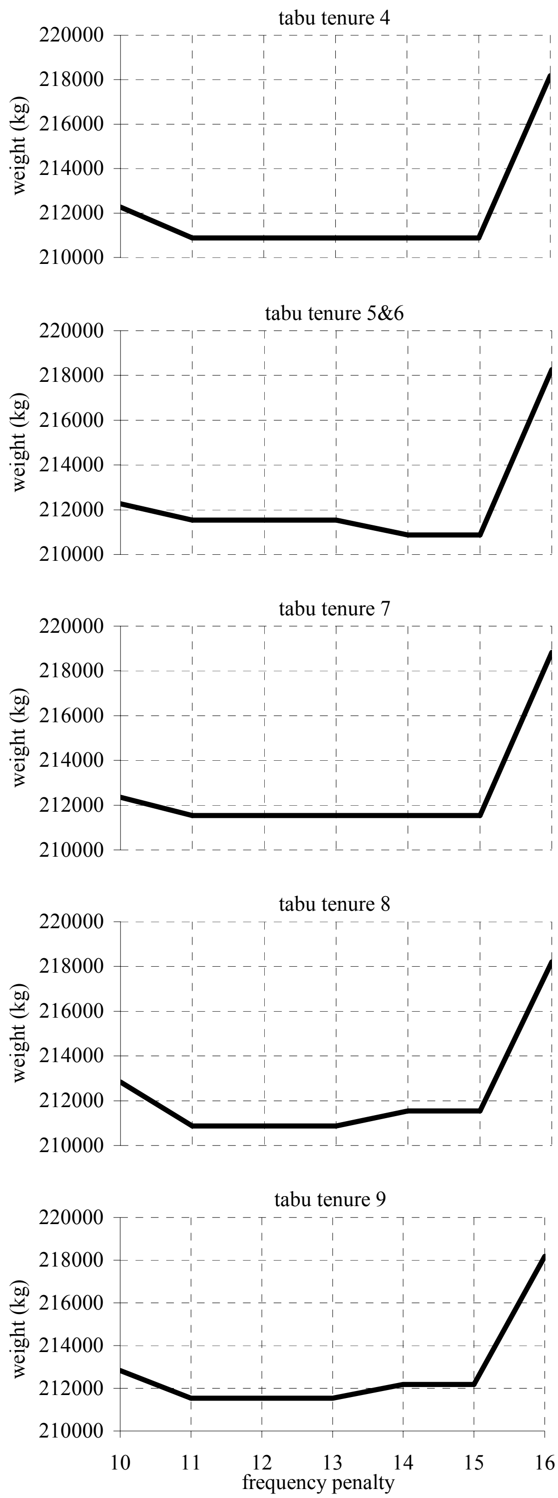

Figure 15. 20-story SAC - Variation of achieved minimum weight with frequency penalty for different tabu tenures, 100 iterations

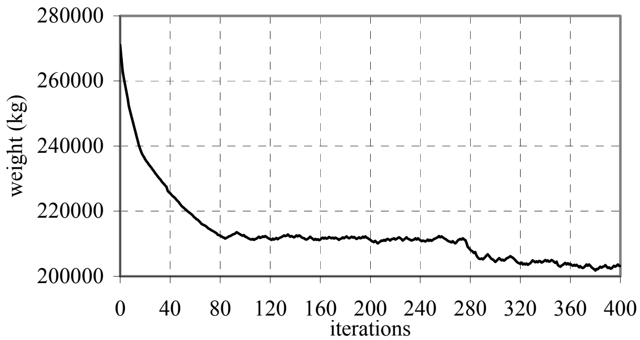

Figure 16. 20-story SAC - Variation of weight with iterations for tabu tenure of 7 and frequency penalty of 13, 400 iterations

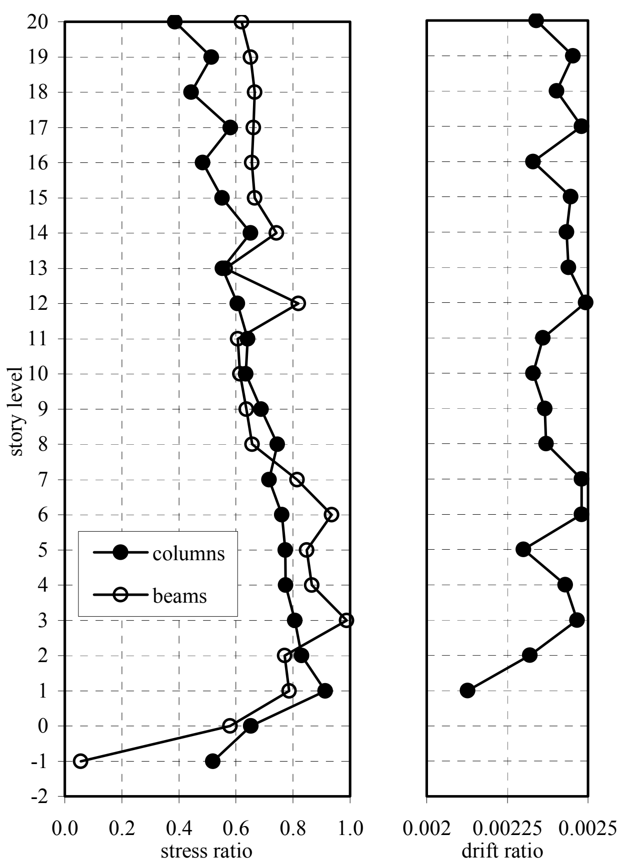

Figure 17. 20-story SAC – Final stress and drift ratios

Frame	Total possible number of permutations	Number of degrees of freedoms	Number of iterations	Total number of analyses	Time
SAC-3	3.56×10^{6}	36	100	327	0:00:31
SAC-9	9.71×10^{28}	184	100	1393	0:06:35
		184	200	3160	0:14:41
SAC-20	2.10×10^{45}	398	100	1920	0:18:44
		398	200	5266	0:49:32
		398	300	8646	1:20:51
		398	400	11587	1:47:31

Table 1. Analysis and design information and time for the case study frames