STRUCTURAL OPTIMIZATION FOR SEISMIC DESIGN

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SUMMARY

The application of Heuristic Search Methods for the earthquake resistant design of structural frames is discussed. The Tabu Search method was selected for application to structural weight optimization of steel moment frame structures. A computer program was developed that uses Tabu Search for weight minimization of two-dimensional framed structures. Written in the FORTRAN computer language, the program performs Tabu Search, structural analysis, and structural design in an iterative procedure. The program has been used to optimize the weight of several frames of varying height including a nine-story, five bay moment frame that had previously been designed for the lateral force requirements of the 1994 Uniform Building Code.

The method demonstrated its capability for optimizing the weight of this medium size frame in a reasonable amount of time without requiring engineer interface during the search process. The search procedure was able to reduce the structural weight of this frame by 18.3% compared to the original design weight. The seismic performance of the optimized structure was then evaluated by calculating the rotations in the plastic hinges that formed in the structural elements during non-linear time history analyses. The final design obtained by the Tabu Search satisfied the desired Life Safety performance level as outlined in FEMA-273. The Tabu Search design frame was compared to the original design in terms of maximum story plastic hinge rotations, story displacements, and inter-story drift ratios during non-linear time history seismic analyses.

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). 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.

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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 to the whole 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 [1] established some theorems related to rational design of structures, which were further generalized by Michell [2]. In the 1940's and 1950's, for the first time, some practical work in the area of structural optimization was done (Gerard [3] Livesley [4] Shanley [5]). Schmit [6] 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 [7] used the Branch-and-Bound method for the purpose of structural optimization. Goldberg and Samtani [8] 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 [9]. Jenkins [10] performed a plane frame optimization design based on the Genetic Algorithm. Farkas and Jarmai [11] described the Backtrack discrete mathematical programming method and gave examples of stiffened plates, welded box beams, etc. R. J. Balling [12], in the AISC "Guide to Structural Optimization", presents two deterministic combinatorial search algorithms among other optimization methods, 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 have been optimized using the program (Kargahi [13]). 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. One of these frame structures is discussed in detail here.

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 [14]. 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.

In order to overcome this problem, Tabu Search uses recency-based and frequency- based memories. The effect of memory may be reviewed as modifying the neighborhood of the current solution (Glover and Laguna [15]). 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.

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

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}, consider 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 $E_i A_i/L_i$, 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 $E_i I_i/L_i$ terms and therefore I_i terms will appear in the denominator of the K^{-1} matrix elements. For a general frame problem both $\sum c_i A_i$ and $\sum c_i I_i$ (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 [16] 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 [17].

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 [16], 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 [18] are added to the program to further increase the practicality of the final designs.

Case Study

A 9-story (10-story including the laterally supported first floor), 5-bay (one of the bays has moment connection on one side only, see Figure 1) SMRF frame (Figure 2) is considered for optimization using the developed program. This frame (SAC-9) is representative of existing steel structures in the Los Angeles area and was part of a SAC program of study following the Northridge earthquake (Mercado [19]). 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 3. Frequency penalties of 13 and 14 result in the minimum achievable weight. Figure 4 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%. The variation of frame weight in 100 iterations for tabu tenure of 8 and frequency penalty of 13 is shown in Figure 5. 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 6. Figure 7 illustrates average final stress ratios for columns and beams at all story levels. The overall average column and beam stress ratios are 0.492 and 0.704 respectively. The inter-story drift ratios are also shown in Figure 7. 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*.

Figure 1.   9-story SAC – Structural framing and typical floor plan

Figure 2.   9-story SAC – Original frame

Figure 3.   9-story SAC - Variation of achieved minimum weight with tabu tenure for different frequency penalties, 100 iterations
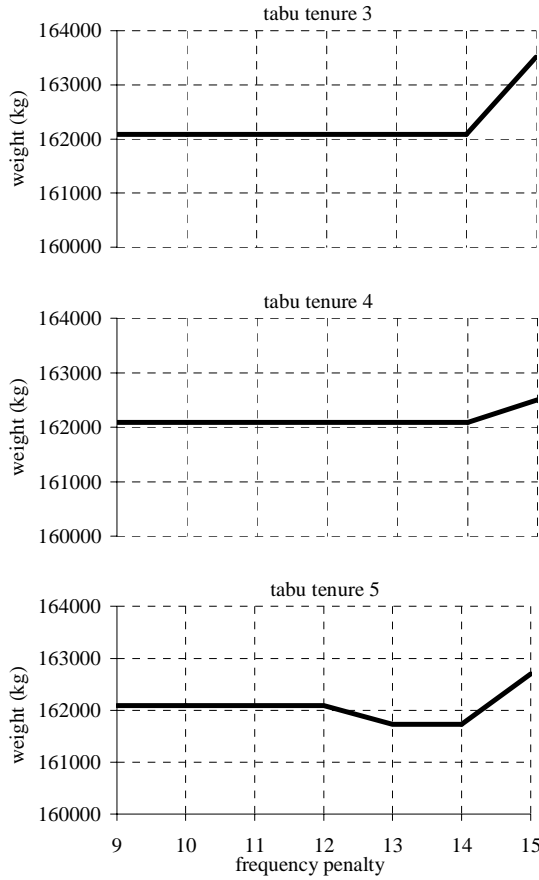
Figure 4. 9-story SAC - Variation of achieved minimum weight with frequency penalty for different tabu tenures, 100 iterations
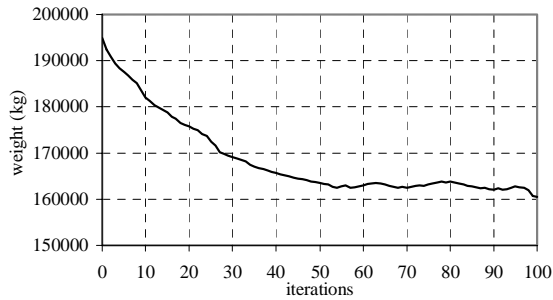

Figure 5. 9-story SAC - Variation of weight with iteration for tabu tenure of 8 and frequency penalty of 13, 100 iterations
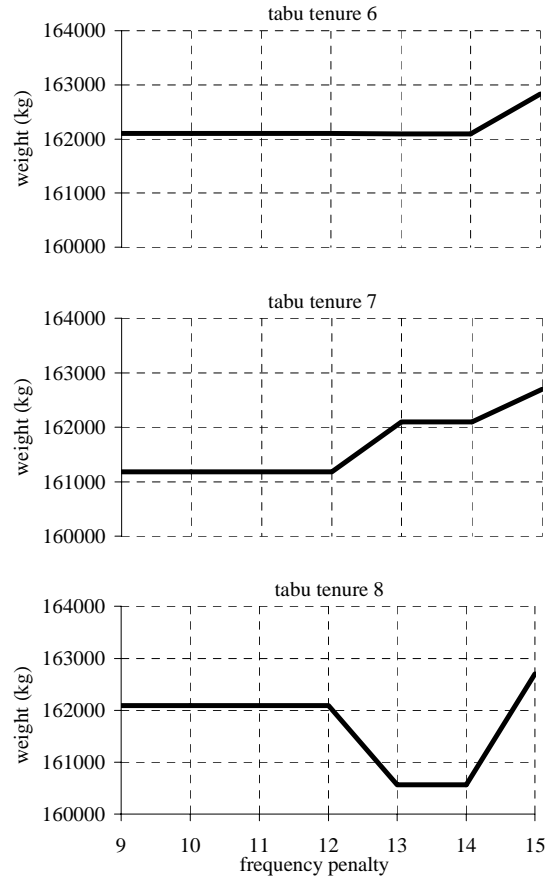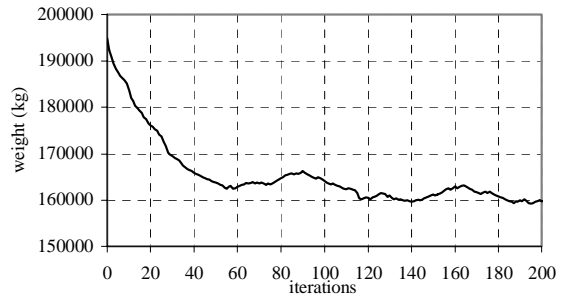
Figure 6. 9-story SAC - Variation of weight with iteration for tabu tenure of 9 and frequency penalty of 13, 200 iterations
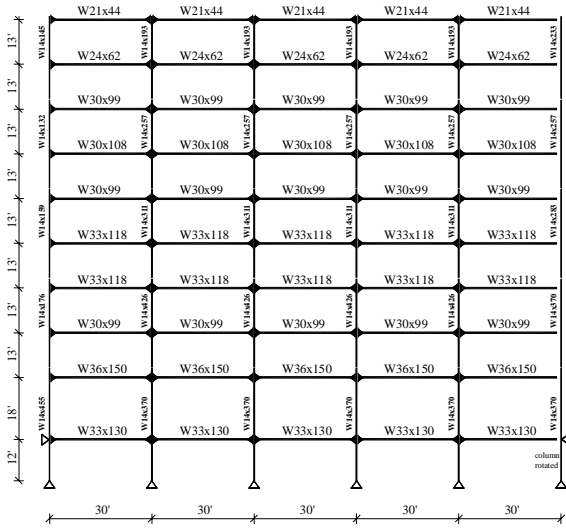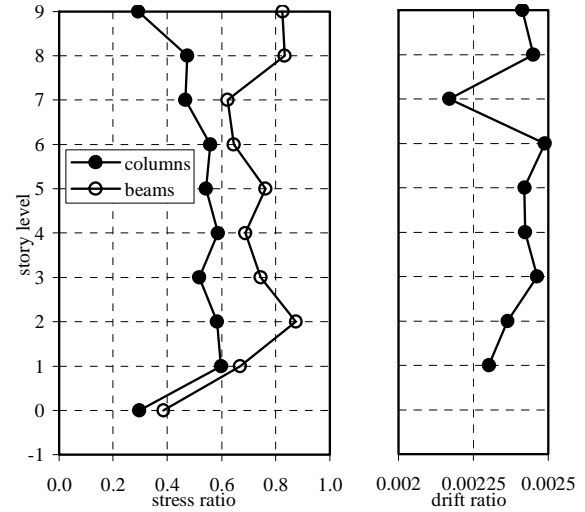
Figure 7. 9-story SAC – Final beam and column sizes

Figure 8. 9-story SAC – Final stress and drift ratios

MODELING ASSUMPTIONS FOR PERFORMANCE MEASUREMENT

In order to obtain a measure of performance for the final outcome of Tabu Search optimization, a series of non-linear time history analyses are performed. The RAM-XLinea computer program [20] is used to study the formation of plastic hinges in the frame elements. Twenty seismic ground motion records developed for the Los Angeles area [21] and with the return probability of 10% in 50 years are used for the analyses. Minimum Life Safety performance is desired for such analyses.

The RAM-Xlinea program is capable of performing non-linear time history analysis for two-dimensional frames. The plastic hinge beam-column element type (type 02) is chosen for modeling the beam and column structural elements. The inelastic behavior is represented by a two-component beam element with concentrated plastic hinges at the ends. The two components are the elastic-plastic component which admits concentrated hinges at the ends, and the infinitely elastic component that allows for strain hardening and gives the combined element a bi-linear character (Figure 9). Yielding takes place only in the plastic hinges. The hinge yield moments can be specified to be different at the two element ends, and for positive and negative bending. The effect of axial force on bending strength is taken into account by specifying P-M yield surfaces. Plastic hinges that yield at constant moment form in the inelastic component. The moment in the elastic component continues to increase, simulating strain hardening. Static loads applied along the element length, or initial forces due to other causes, can be taken into account by specifying equivalent fixed end forces.

Column and beam element stiffness properties are introduced by specifying modulus of elasticity, strain-hardening ratio, cross sectional area, and moment of inertia. The yield surface for the columns is introduced by specifying positive yield moment, negative yield moment, compression yield force, tension yield force, M/M_y+, P/P_y+, M/M_y-, and P/P_y-, as shown in Figure 10. For beams only the yield moments are introduced.
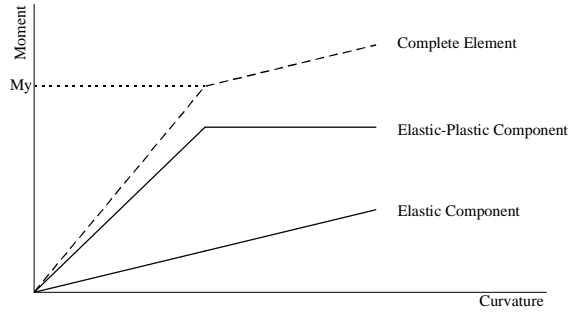
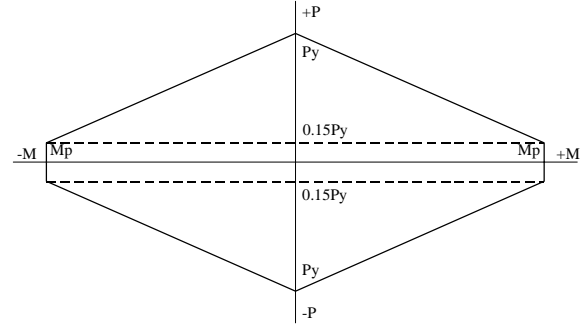**Figure 9.** **Non-linear element parallel components**

Figure 10. Column P-M interaction diagram

FEMA 273 seismic rehabilitation guidelines [22] provides acceptance criteria for the desired performance level for different types of structural systems. The ratio of plastic rotation over yield rotation, θ_p/θ_y, is used to measure the performance of fully restrained steel moment frames. This ratio is limited to 7 for beams and columns with $P/P_{ye} < 0.20$, if $b_f/2t_f < 52/\sqrt{F_{ye}}$, when Life Safety performance is desired.

The value of yield rotation of beams in FEMA 273 is given as

$$\theta_y = \frac{ZF_{ye}L_b}{6EI_b}$$

and for columns is given as

$$\theta_y = \frac{ZF_{ye}L_c}{6EI_c}(1 - \frac{P}{P_{ye}})$$

where
b_f is the flange width,
t_f is the flange thickness,
Z is the plastic modulus of the section,
F_{ye} is the yield strength of the steel material,
L_b is the beam length,
E is the elasticity modulus of the steel material,
I_b is the beam moment of inertia,
L_c is the column length,
I_c is the column moment of inertia,
P is the column axial force,
and P_{ye} is the column compression yield force.

PERFORMANCE OF THE CASE STUDY STRUCTURE

The SAC structure studied for optimization, was modeled using RAM-Xlinea and analyzed for twenty, 10% in 50 years, ground accelerations. Plastic rotations at the formed non-linear hinges for all elements and all analyses are read and their maximum is compared with the yield rotation capacity of the elements. Figure 11 shows maximum plastic rotations of beams at each story level for all ground motions for the SAC-9 frame. Figure 12 illustrates maximum $\theta p/\theta y$ ratios for beams at each story level in the SAC-9 frame.

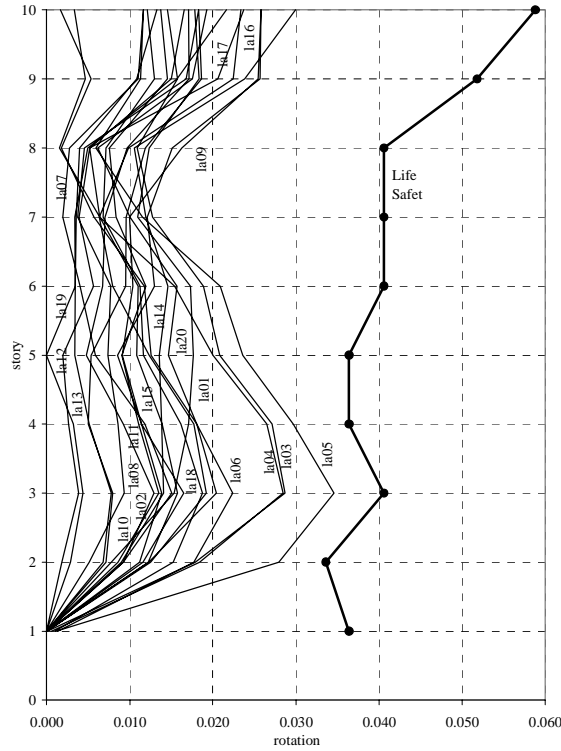**Figure 11.   9-story SAC – Maximum plastic rotation of beams for different ground acceleration records, TS design**
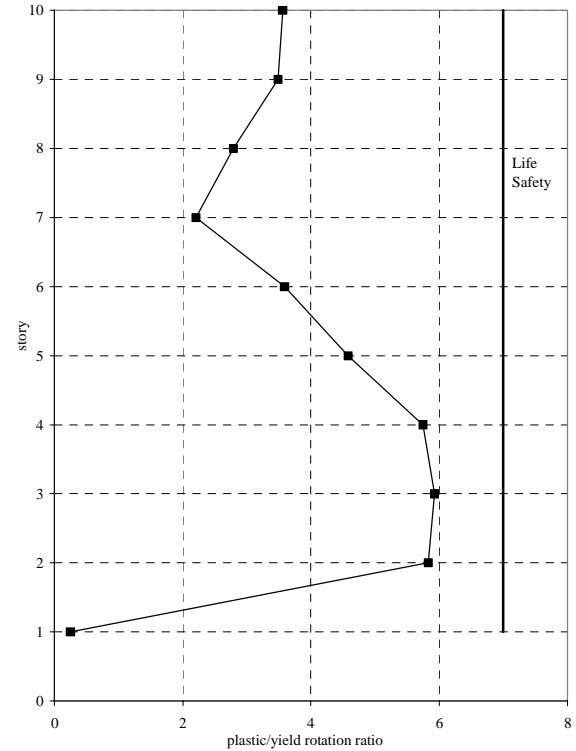

Figure 12.   9-story SAC – Maximum θ_p/θ_y ratios for beams, TS design

The analysis indicates that the Tabu Search (TS) optimization final design for the 9-story SAC structure satisfies the performance-based regulations of FEMA273 at the Life Safety level with regard to the plastic hinge rotations of its elements. Plastic rotations in the columns are either zero or negligible. Maximum θ/θ_y ratio for the beams is 5.93 which is well below the value of 7 for Life Safety.

COMPARISON OF THE TABU SEARCH DESIGNS AND THE ORIGINAL DESIGNS

In order to compare the TS final design with the original design, the original design frame was analyzed for the ground motion records that resulted in the largest plastic hinge rotations for the TS design. The values of maximum story plastic hinge rotations, story displacements and inter-story drift ratios are then compared against the corresponding values from the analyses of the TS design frames.

The original design 9-story frame is analyzed using the LA05 ground motion record that produced the most severe effects on the lower half, and the LA16 ground motion record that produced the most severe effects on the upper half of the TS Design frame. Figure 13 shows the values of maximum beam plastic rotations, maximum story displacements, and maximum story drift ratios at different story levels of the SAC-9 frame obtained from the original and TS designs under LA05 base acceleration. The values of plastic beam rotations are larger for the TS design at the lower floors. The maximum top floor displacement of the TS design reaches 0.945 m (37.2 in) while the comparable one from the original design is 0.711 m (28.0 in). The drift ratios are generally higher for the TS design under this ground acceleration. The maximum drift ratio is 0.0385 at the 4th floor level of the TS design and 0.0297 at the 3rd floor level of the original design. Figure 14 shows the values of maximum beam plastic rotations, maximum story displacements, and maximum story drift ratios at different story levels of the SAC-9 frame as obtained from the original and TS designs under LA16 acceleration. The beam plastic rotation demands

are very comparable for the two designs under this ground motion. Maximum rotation demand for the original design occurs at the 7th and 8th levels while maximum values for the TS design occurs at the 9th and 10th levels. In both designs, there is no significant plastic rotation in the columns. The maximum top floor displacement of the original design reaches 0.594 m (23.4 in) while the one from TS design is 0.564 m (22.2 in) with the upper story levels of the original design frame generally having a larger displacement. The maximum drift ratio is 0.0306 at the 10th floor level of the TS design and 0.0231 at the 9th floor level of the original design. The larger drift ratios of the original design occur in the story levels 5, 6 and 7, whereas the larger drift ratios of the TS design occur in the story levels 8, 9, and 10.
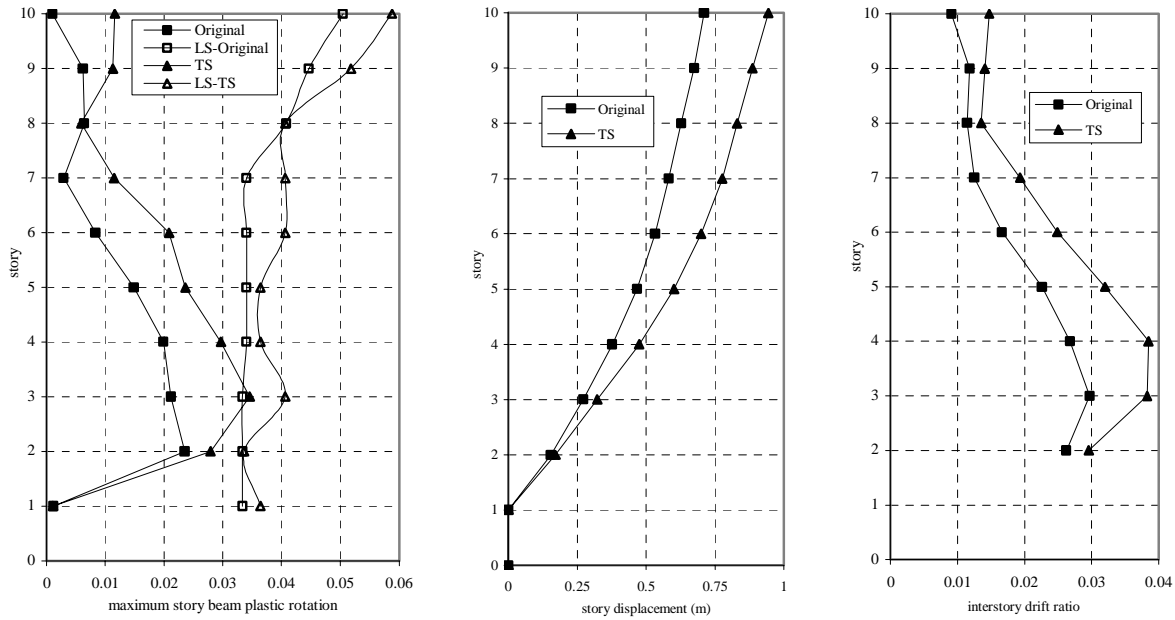

Figure 13.   9-story SAC - comparison of TS and original designs for LA05 record, LS=Life Safety
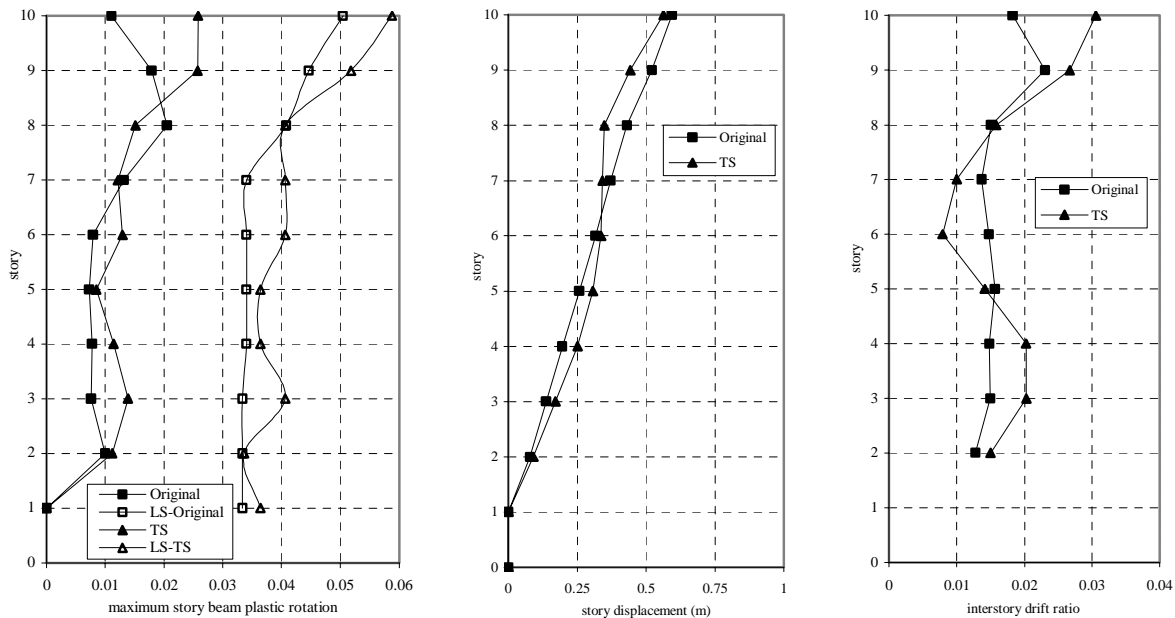

Figure 14.   9-story SAC - comparison of TS and original designs for LA16 record, LS=Life Safety

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 case study structure, a 9-story,5-bay frame, resulting in 18.3 weight reductions. Similar to the original design, the final Tabu Search designs of the 9-story frame was displacement controlled.

The frame being studied was analyzed and designed using a personal computer with an Intel Pentium II, 233 MHz processor that is relatively slow by current standards. The program was able to achieve significant weight reductions in a reasonable time. Sample run times for 100 and 200 iterations were 7 and 15 minutes respectively. The total possible number of permutations based on the available sections for beams and columns was 9.71×10^{28}. Samples of the number of analyses performed by the program for 100 and 200 iterations were 1393 and 3160 respectively which represent a very small fraction of the total possible permutations.

The TS final design satisfied the desired Life Safety performance level as outlined in FEMA 273 in non-linear time history analyses. The plastic rotations of beam and column elements stayed well below the limiting values for such performance level.

The behavior of the TS frame was comparable with the original design in terms of its maximum plastic hinge rotations, story displacements, and inter-story drift ratios in non-linear time history analyses. The design of the buildings is primarily controlled by displacement constraints under service loads. This tends to give this building an overstrength relative to code specified lateral force. This is reflected in the low beam plastic rotations for the 9 story building even with the smaller beam and column section which were the result of the Tabu Search optimization.

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