PERFORMANCE OF 2D FRAME OPTIMIZATION CONSIDERING THE SEQUENCE OF COLUMN FAILURE MECHANISM USING GA-SAP2000

By Mohammad Ghozi

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ABSTRACT

Many constraints must be considered in steel structure design due to the code requirements and practical aspects like strong column weak beam, soft story, column's plastic modulus and column's position. The purpose of this paper is to discuss differences between result of optimization with strong column weak beam, column's plastic moment and column position as constraints. Optimization processes are carried out through 30 members of 2D steel structure model using genetic algorithm-SAP2000.Performance of two optimized structures are presented by conducting nonlinear static analysis. Optimized structure's data are analyzed such as structure weight, displacement, pushover curve, ductility, columns plastic modulus, column cross section area and beam to column flexural strength ratio The second objective function which considered five constraints can produce 81.25% lighter and 1.765 times more ductile than the other one. It is concluded that optimization considering the sequence of column failure mechanism is very useful and should be included in every design of steel structure.

Keywords: Optimization, Steel structure, Strong column weak beam, column plastic modulus.

INTRODUCTION

The current design methodology in the AISC Seismic Provisions (AISC, 2002) requires that the inter story drift of a steel moment frame be accommodated through frame deformations. The inelastic deformations are provided through development of plastic hinges at pre-determinated locations within a frame. When fixed moment connections are used, the plastic hinges are developed through inelastic flexural deformations in the connecting beams and in the column panel zone. This results in a strong column, strong connection and weak beam design philosophy. The AISC LRFD 1999 (AISC, 1999) has determined the ratio of flexural strength so that structures have "strong column weak beam" (scwb) behaviour. With this requirement, columns should be stronger in flexural strength than beams at every joint. (AISC, 1999).

The application of genetic and evolutionary computation to the automated design of structures has followed several avenues. There have also been research efforts devoted to developing algorithms for optimized structure topology to satisfy user-determined natural frequencies. The second major area of automated design using genetic algorithms has been their application for optimal member sizing for truss structures using linear elastic analysis with U.S. design specifications (Adeli & Sarma, 2006). But the fitness method can't differentiate between one structure with one failure in the bottom column and the other structure with one failure in the top column.

The final major application of genetic algorithms (GA) is the automated design of steel frame structures. One excellent method was combining commercial finite element method (FEM) program with iteration method to find required area of steel reinforced concrete plate (Khennane, 2007) and commercial FEM program with GA in parallel computing method (Ghozi, et al, 2011).

Since the advantage of commercial FEM programs are well known for structure's design and its combination with GA is possible, it will be good for using combination of commercial FEM-GA for research in optimization. For this reason, it will be discussed the difference between optimization result with and without constraints such as "strong column weak beam"constraint, column position constraint and column's plastic modulus constraint. Nonlinear static analysis will be conducted to check the performance of two different optimization results.

THEORIES

Nonlinear static analysis

Pushover analysis is a static, nonlinear procedure in which the magnitude of structural loading is increased with a certain pattern. With this loading, weak links and failure modes of structure will be found. The loading with effects of cyclic behavior and load reversals are estimated by force-deformation criteria and damping approximations (Habibullah, 1998).

The ATC-40 and FEMA 356 documents have developed modeling procedures, acceptance criteria and analysis procedures for pushover analysis. These documents define criteria for hinges used in this method. Two points labeled A, B, C, D and E are used to define force deflection behavior of the hinge and three points labeled IO, LS, and CP are labeled to define the acceptance criteria (IO, LS and CP stand for Immediately Occupation, Life Safety and Collapse Prevention, respectively) (see figure 1). The FEMA 356 code is used in this paper for finding the target displacement of analyzed structures.

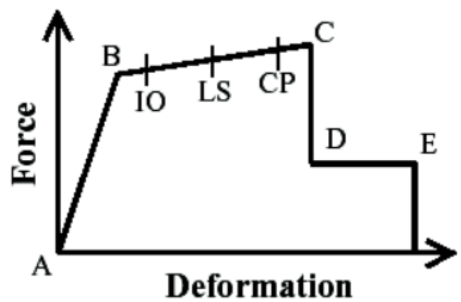

Figure 1. Force-deformation for pushover hinge (Habibullah, et al, 1998).

Strong column weak beam concept

The current design methodology in the AISC Seismic Provisions (AISC, 2002) requires that the specified interstory drift of a steel moment frame be accommodated through a combination of elastic and inelastic frame deformations. The inelastic deformations are provided through development of plastic hinges at pre-determined locations within the frame. When moment connections are used, the plastic hinges are developed through inelastic flexural deformations in the connecting beams and in the column panel zone. This results in a strong column and weak beam design philosophy (AISC, 1999). This code requires that the sum of column flexure strengths at a joint should be more than the sum of beam flexure strengths (AISC SEISMIC 1, 9.6).

Column failure mechanisn concept

The engineer usually place stronger column below the column at upper story. The stronger column can be seen as the bigger value of cross sectional area (A), column's depth (H), elasticity modulus (E), plastic modulus (Z33) or radius of gyration (from the same yield strength). Since the strong column weak beam concept based on the plastic modulus, so the plastic modulus is considered to arrange the columns from lower story to the top story.

Usually the optimization methods pursue the best profile configuration of structure but disregard the above mentioned problem. The fitness method can't differentiate between one structure with one failure in the bottom story column and the other structure with one failure column in the top story. So it is necessary to make one multiplier as constraint so that the failure at lower column is avoided.

Sap2000

SAP2000 structure analysis program is a finite element analysis tool which already used for analyzing and modeling structure. SAP2000 could process or import the file input with extension MDB, XLS, TXT and SDB. SAP2000 also could export analysis result and design to files with extension XLS, TXT and SDB. After input file being opened, SAP2000 will run analysis, save the results and design of all members and create output file (Computer and structures, Inc.,2000). From the output file, we can get the required data such as frame stress and joint displacements as indicators for acceptance criteria (Ghozi, et al, 2011).

Simple Genetic Algorithm

GA, is a population-based global search technique based on the Darwinian theory (Goldberg, 1989). Common operators used in GA are initialization of population, evaluate population, selection, mating, crossover, mutation, stopping criteria and get results (Gen & Cheng, 1997). The preliminary approach of GAs is Simple Genetic Algorithm (SGA). SGA guides the evolutionary search by a single population *Pi*. The size of *Pi* is denoted by *SP*. Individuals are encoded in a string scheme associated with one of the codes of the binary, integer, and real. In the evolutionary search, the promising individuals $Pi-sel$ and $Pi+1-sel$ are chosen from the population by a selection operation (roulette wheel, stochastic universal sampling, ranking, truncation, etc.). Then, the individuals chosen are applied to recombination and mutation operation (one point or multipoint crossover and mutation, uniform crossover, etc.). These evolutionary operations (mutation mut, crossover *cr*, and selection *sel*) are governed by their related evolutionary parameters *Par* (mutation and recombination probability rates, selection pressure, etc.). The population *Pnew* evolved by the application of these evolutionary operators is decoded. Then, the fitness values are computed by use of this population. The evolutionary search is executed to transmit (migration) the individuals (emigrant and immigrants) to the next populations until satisfying a predetermined stopping criteria (Gen & Cheng, 1997; Haupt, 2003).

Simple GA and SAP2000

Since the structure is simple, GA procedures are processed in Single PC. Optimization problems are solved by using combination of SAP2000 and simple GA (Ghozi, et al, 2011) (see Figure 2).

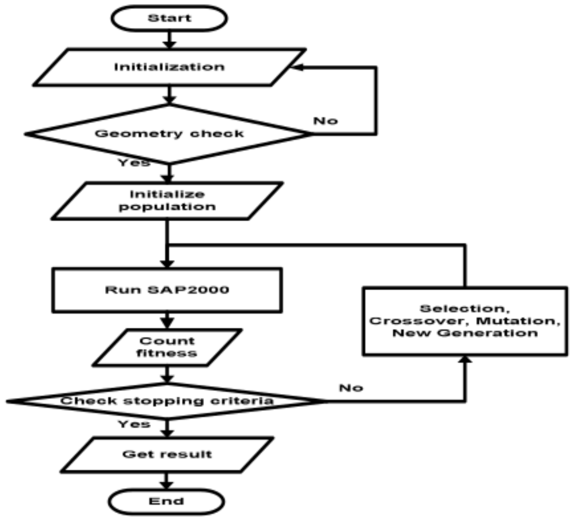

Figure 2. GA-SAP2000 Flowchart in single PC (Ghozi, et al, 2011).

After initial population is created, the program commands PC to 1) run SAP2000, 2) analyze input files, 3) design the input files, 3) close SAP2000. Each input file must have one output file. The message is to let PC to evaluate and calculate fitness value of each output file (see Figure 2). Raw data for of drift calculation are taken from "Joint Displacements" table. Data for stress constraint calculation are taken from "*Steel Design 1 – Summary Data AISC-LRFD99" Sap2000 output file table*. Raw data for strong column weak beam ratio are taken from "Frame Section Properties 01 – General" *Sap2000 output file table*. This iteration is processed until the generation reach 40. The specific generation number is used as the stopping criteria.

STEEL STRUCTURE MODEL FOR OPTIMIZATION

A 2D structure under a single load case is shown in Fig. 1 below. This frame is designed according to AISC-LRFD specification and uses a displacement constraint (story drift < story height/300). The load values presented in Fig. 3 are assumed to define the service-load level. The effective length factors of the members are calculated as $K_x \geq 1.0$ for a sway-permitted frame. Fabrication conditions are imposed to group together the relative sizes of the member cross sections. Beam members are required to remain the same size for three consecutive stories, excluding the top story beam. Similarly, the columns are required to remain the same over two stories. The total number of design variables is nine (Pezeshk, et al, 2000).

The out-of-plane effective length factor for each column member is specified to be $K_y = 1.0$, while that for each beam member is specified to be $K_y = 0.2$ (i.e., floor stringers at 1/5 points of the span). The length of unbraced compression flange for each column member is calculated during the design process, while that for each beam member is specified to be 1/5 of the span length (Pezeshk, et al, 2000).

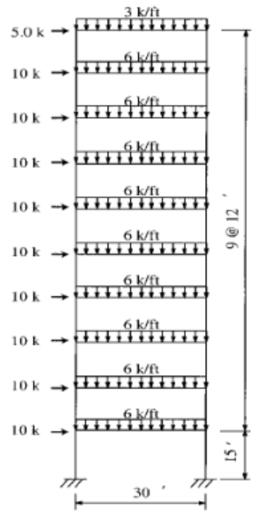

Figure 1. 2D steel structure model (Pezeshk, et al, 2000)

About 256 types of WF profiles used as available profiles are taken from SAP2000 database. Two objective functions are compared in this paper. The first objective function is to minimize the weight of structure subjected to two constraints (stress constraint and displacement constraint) :

$$Objfunc1 = Min.(\sum \rho_i A_i L_i)\,(1+\sum re_i + \sum rj_j) \tag{1}$$

And the second objective function is to minimize the weight subject to four constraints (stress constraint, displacement constraint, scwb constraint and column plastic modulus constraint):

$$Objfunc2 = Min\,(\sum \rho_i A_i L_i)\,(1+cp\sum re_i + \sum rj_j + \sum scwb_j + \sum cpm_j) \tag{2}$$

i = 1 to 30 is element number
j = 1 to 10 is joint number at left column

Where *Objfunc* is an objective function, ρ is a unit weight, A is an area of cross section, L is a length of element, cp is a column position constraint, re_i is a element capacity constraint, rj_j is displacement constraint, $scwb_j$ is flexural strength constraint, and cpm_j is column's plastic modulus constraint. The $re_i = 0$ if $ratio_i < 1$ and $re_i = ratio_i^2$ if $ratio_i > 1$, $rj_i = 0$ if $drift_i < 0{,}04672$ and $rj_i = drift_i^2$ if $drift_i > 0{,}04672$, $scwb_k = 0$ if $R_j < 1$ and $scwb_j = R_j^2$ if $scwb_j > 1$, $cpm_j = 0$ if $RZ_j < 1$ and $cpm_j = RZ_j^2$ if $RZ_j > 1$. The cp = 1 if re_i is for beam, and cp=column level story if re_i is for column.

For displacement constraint, the interstory drift is limited to 0.004 times the story height. For stress constraints, the capacity ratio of each element is limited to equation (H1-1 AISC-LRFD99):

$$\text{ratio} = \frac{P_u}{\varphi P_n} + \frac{8}{9}\left\{\frac{M_{u33}}{\varphi b M_{n33}} + \frac{M_{u22}}{\varphi b M_{n22}}\right\} \text{ for } \frac{P_u}{\varphi P_n} \geq 0.2 \tag{3}$$

$$\text{ratio} = \frac{P_u}{2\varphi P_n} + \left\{\frac{M_{u33}}{\varphi b M_{n33}} + \frac{M_{u22}}{\varphi b M_{n22}}\right\} \text{ for } \frac{P_u}{\varphi P_n} < 0.2. \tag{4}$$

Where P_u is the required compressive strength, P_n is the nominal compressive strength, M_u is the required flexural strength, M_n is the nominal flexural strength, φ = 0:85 and φb = 0,9.
For the flexural strength constraint, the ratio of beam to column stiffness at every joint must under 1, is given by 9.6 AISC Seismic:

$$R_j = \frac{\sum_{n=1}^{nb} M_{pbn}}{\Sigma M_{pc}} < 1. \quad (5)$$

Where R is strong column weak beam ratio, M_{pbn} is plastic moment of beams, M_{pc} is plastic moment of columns above and below the joint.

For the column's plastic modulus constraint, the ratio of column's plastic modulus at every joint must under 1:

$$RZ_j = \frac{Z33\ of\ column}{Z33\ of\ column\ at\ lower\ column} < 1. \quad (6)$$

Where Z33 is column's plastic modulus.

GA process are carried out with parameters: 30 individuals, 40 generations, 0,8 crossover, 0,005 mutation, 1 cut point crossover, 25% elitism and the rest use roulette wheel selection. Nonlinear static analysis is then used to test 2 optimized structures.

RESULT AND DISCUSSION

Optimization of the 2D brace has done successfully with 2 different objective functions. The chosen individual is the highest fitness value from 40th generation and the W profiles are displayed in Table 1 below. Both two optimized structures have zero element and displacement constraint violation. The Objfunc2 has 81.25% lighter structure weight than objfunc1. However objfunc1 has smaller maximum lateral displacement than objfunc2.

Table 1. Optimization result

Story	Objfunc1		Objfunc2	
	Column	Beam	Column	Beam
1	W14X370	W40X431	W14X605	W40X149
2	W14X370	W40X431	W14X605	W40X149
3	W18X234	W40X431	W14X257	W40X149
4	W18X234	W33X169	W14X257	W36X135
5	W12X279	W33X169	W14X257	W36X135
6	W12X279	W33X169	W14X257	W36X135
7	W12X279	W24X146	W14X193	W21X132
8	W12X279	W24X146	W14X193	W21X132
9	W14X211	W24X146	W18X106	W21X132
10	W14X211	W14X90	W18X106	W30X99
Weight (kip)	138.074		112.185	
Maximum lateral displacement (ft)	0.717549		0.890026	

Ideally, lower story should have bigger column cross section area and plastic modulus than higher story. Both Objfunc1 and Objfunc2 has bigger column plastic modulus for lower story. But there is problem for Objfunc1 in column cross section plot. Objfunc1 column cross section area at story 5 to 8 are bigger sthan at story 3 and 4. Contrary to Objfunc1, Objfunc2 always has columns in which getting bigger cross section area in lower level. It means objfunc2 structure has stronger columns than obj1 structure (see Figure 4 below). It can be concluded that objfunc2 has better column arrangement than objfunc1 structure.

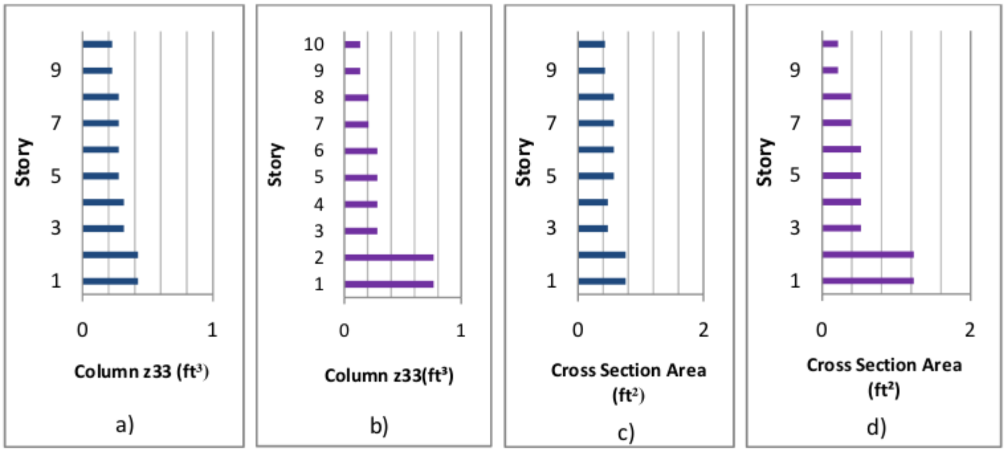

Figure 2. a) Column z33 of Objfunc1 b) Column z33 of Objfunc2 c) Column cross section area of Objfunc1 d)Column cross section area of Objfunc2

According to 9.6 AISC Seismic, All ideal structures have flexural beam to column flexure strength ratio under 1 at all joints. Flexural strength as represented by strong column weak beam ratio plotted on Figure 5 below. At level 1 through 3, objfunc1 has scwb ratio more than 1, but objfunc2 has all scwb ratio under 1. It means objfunc2 structure has "strong column weak beam" behavior as required by AISC Seismic. Objfunc1 has stronger beam than column at level 1 to 3, so Objfunc1 has "strong beam weak column" behavior. It can be concluded that objfunc2 can produce structure which has a "strong column weak beam" behavior.

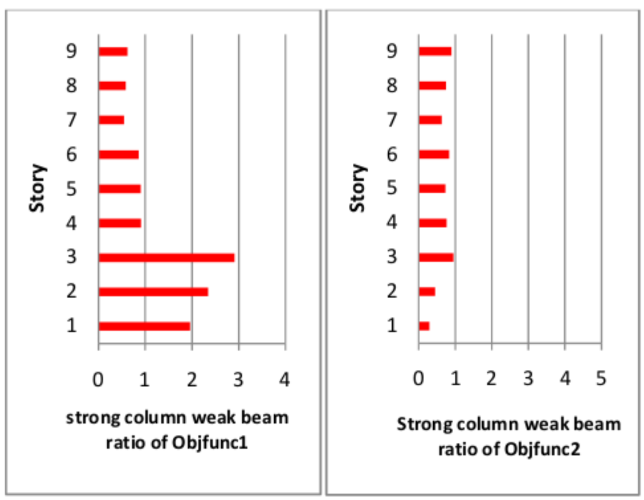

Figure 3. Strong column weak beam ratio.

Objfunc1 has bigger base force (978.137 kip) than objfunc2 (690.263 kip). The highest displacement is from objfunc2 (3.999 ft) and the shortest is from Objfunc1 (0.5454 ft) (see figure 6). The biggest base force is taken by the structure with heavier structure weight because the base force is taken by structure weight. The highest displacement can be found at structure with good arrangement dimension like column's plastic modulus and beam to column flexural strength ratio as it is founded at Objfunc2 structure.

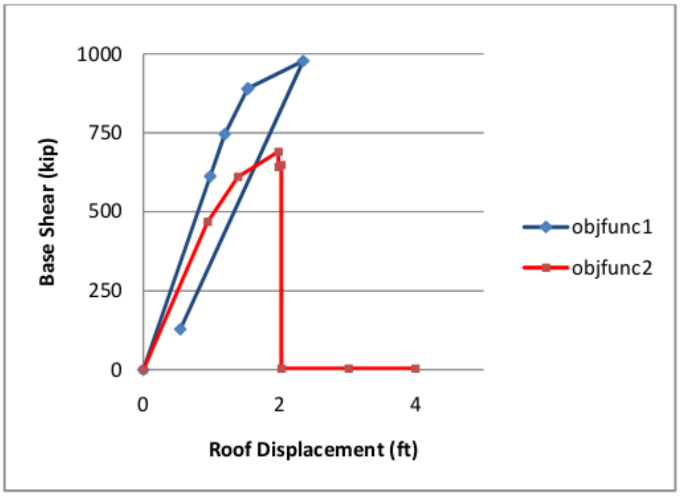

Figure 4. Pushover curve.

FEMA 356 Coefficient method is used to find the target displacement values. This value represents performance of structure during seismic loading. The ductility can be determined from maximum rupture displacement devided by first yield displacement. Objfunc1 has the biggest target value (69.652 kip and 0.107 ft) than Objfunc2 (51.634 kip and 0.104 ft) (see Table 2). Ductility of objfunc2 is 4.2173, in which 1.765 times the ductility of Objfunc1 (2.38926).The best ductility is found at Objfunc2 structure which has all beam to column flexural strength ratio under 1 and well arrangement column plastic modulus.

Table 2. Ductility and Target Displacement due to FEMA 356 coefficient method.

	Ductility	Target displacement	
		Kip	ft
Objfunc1	2.389264	66.504	0.107
Objfunc2	4.217301	51.634	0.104

CONCLUSION

Optimization proces have been completed to compare with and without consideration of the sequence of column failure mechanism. A new objective function (Objfunc2) is introduced to consider the sequence of column failure mechanism. It is found that not only the arrangement of column is better but it gives a more lighter (81.25%) and more ductile (1.765) than common used objective function (Objfunc1). It is concluded that optimization considering the sequence of column failure mechanism is very useful and should be included in every design of steel structure.

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