Optimization of seismic behavior of steel frames with semi-rigid connection using genetic algorithm

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Abstract
In analysis and design of steel frame, beam-column connection has a significant role. In this paper, a genetic algorithm has been used for non-linear analysis and design of steel frames. For minimizing the weight of frame by satisfying the applied constraint and restraints such as amount of axial and combined stresses, criteria such as target displacement, number and location of plastic hinges were used. To analyze and designing the frame elements, I and Box shaped standard sections have been used for beams and columns, respectively. Finally, semi-rigid connection stiffness allocated to the beam to column connection has been obtained. The results show that non-linear analyses give less weight for short period frames with semi-rigid connection. But by increasing period of frames least weight are obtained in non-linear analysis with semi-rigid connections.

_Keywords_: optimization, genetic algorithm, semi-rigid connection, non-linear analysis, plastic hinge

1 Introduction
The researches have shown that the moment–rotation (M-θ) relationships for some of the connections are nonlinear, and the assumption of a constant value for stiffness of connection is not real because it changed by increasing load levels. Laboratory test results have shown that the beam to column connection is neither complete articulated nor complete restraint, rather it is in the form of semi-rigid (semi-restraint). Therefore, for accurate response of the structural behaviour, it is necessary considering the structure connections in the form of semi-rigid with nonlinear behaviour.

This paper presents a genetic algorithm based on optimum design method for reducing the weight of steel frames and obtains the rigidity of connection in a state where the structure has been reached its least weight. The results in 4 states of rigid connection with static linear analysis, semi-rigid connection with static linear analysis, rigid connection with non-linear analysis and semi-rigid connection with non-linear analysis are compared.

2 Optimization of Steel Frames with Semi-Rigid connection
Since inelastic behaviour is intended in most structures subjected to infrequent earthquake loading, the use of nonlinear analyses is essential to capture behaviour of structures under seismic effects.

The following constrains have been used in the frame design and optimum procedure:
2.1 Control of interactive stresses in the elements (bending stresses + axial stresses)

The combinations of axial and bending stresses of the members are calculated. For members subjected to both axial compression and bending stresses, we have:

\[
C_i = \left( \frac{\sigma_{axial}}{\sigma_{axial\ allow}} + \frac{\sigma_{bending}}{\sigma_{bending\ allow}} \right)^{-1} , \quad i = 1, ... nm
\]  

(1)

\[C_{1i} \geq 1 \rightarrow \alpha_{1i} = C_{1i}^2\]  

(2)

\[0 < C_{1i} < 1 \rightarrow \alpha_{1i} = C_{1i}\]  

(3)

\[0 \geq C_{1i} \rightarrow \alpha_{1i} = 0\]  

(4)

For calculating the fitness factor of interactive stress of frames, sum the fitness of each individual element were used:

\[C_i = \sum_{i=1}^{nm} \alpha_{1i} , \quad i = 1, 2, ... nm\]  

(5)

2.2 Control of relative displacement of the stories (Drift)

The story drift is defined as the difference of maximum lateral displacements of any two adjacent floors. Some limiting requirements are needed for the interstory and top deflections of buildings in the earthquake regulations. The maximum interstory drift and top deflection of building is restricted to earthquake resistant codes. It is not to exceed a certain percentage of the building height.

\[\text{if } T \leq 0.7 \text{sec } \rightarrow \quad \frac{\delta_{n+1} - \delta_{n}}{h} \leq \frac{0.025}{0.7R}\]  

(6)

\[\text{if } T > 0.7 \text{sec } \rightarrow \quad \frac{\delta_{n+1} - \delta_{n}}{h} \leq \frac{0.020}{0.7R}\]  

(7)

Were \(\delta_{n+1} - \delta_{n}\); is the difference of the deflections between the two neighboring floors, \(h\) is story height, \(T\) is the fundamental period of building and \(R\) is the structural response modification factor (Iranian Earthquake resistant code, standard No 2800-3rd edition)

\[C_{2i} = \sum_{i=1}^{ns} \frac{\delta_{inter,drift}}{\delta_{allow,drift}} , \quad i = 1, 2, ... nstory\]  

(8)

\[C_{2i} \geq 1 \rightarrow \alpha_{2i} = C_{2i}^2\]  

(9)

\[0 < C_{2i} < 1 \rightarrow \alpha_{2i} = C_{2i}\]  

(10)

\[0 \geq C_{2i} \rightarrow \alpha_{2i} = 0\]  

(11)

To calculate the fitness factor of interstory drift of frames, the fitness of each interstory was added up.

\[C_2 = \sum_{i=1}^{ns} \alpha_{2i} , \quad i = 1, 2, ... nstory\]  

(12)
2.3 Number of plastic connections created in the elements

Plastic hinge formation is a tool that is used in seismic analysis for determining the inelastic capacity of structural members. The ultimate performance of structure depends on location, number, capacity and behaviour of plastic hinges. In this paper lumped plastic hinge which idealized by FEMA356 were used.

Number of plastic hinges are affected the collapse mechanism of model frames. For improving the response of steel frame and achieving a more ductile capacity, it is better to shift the possible location of the plastic hinge away from column and connection.

The constraints of combination stresses and relative displacement of stories have been considered according to the regulations of earthquake resistant building code and the constraint of maximum formation of plastic connection in elements (preferably in beams) as well as the regulations of allocation of connection to frame elements have been considered according to the FEMA-356 recommendation.

For nonlinear static analysis (pushover), a combination of the capacity spectrum method (CSM) suggested in ATC-40 and the displacement coefficient method (DCM) suggested in FEMA-356 were used.

A number of methods have been proposed for seismic design of structures by investigators in the past. Many traditional procedures for seismic design of building have been developed. Some of these are the force-based design (FBD) method, direct displacement-based seismic design DDBD, capacity spectrum methods, energy method and equal drift. In this paper, for optimum design of steel structure, formation and location of plastic hinges were also in addition to the fore mentioned. This method is a simple and as efficient approach for representing inelasticity in frames.

The fitness factor of plastic hinge depends on the ratio of beam and column elements. Thus, hinge number to whole beam and column element could be defined. In this paper, for each element, two plastic hinges are defined and location of hinge is approximately 0.5 times the element depth.

\[
C_i = \frac{\sum_{i=1}^{n_b} NH_b}{MAX(NH_b)} - \frac{\sum_{i=1}^{n_c} NH_c}{MAX(NH_c)}
\]  

(13)

Therefore, for fitness factor of each frame the following expression was used:

\[
C = b_1 * C_1 + b_2 * C_2 - b_3 * C_3
\]  

(14)

In this paper for b1, b2, b3 after many trial analyses, the value of 1.15, 1.3 and 1.10 were chosen respectively. The discrete optimum design problem of nonlinear steel frames with semi rigid connection where the minimum weight is considered as the objective can be stated as follows:

\[
W = \sum_{i=1}^{nm} A_i \rho_i l_i
\]  

,  

\[i=1,2,....nm\]  

(15)

In Eq.15, \(A_i\) is cross-sectional area of member, \(\rho_i\) and \(l_i\) are density and length of member. The unconstrained function \(F\) can be expressed as:

\[
F = 3 \left(\frac{10000}{W \times (1 + C)}\right)
\]  

(16)

In Eq. 16, \(W\) is the weight of structure and \(C_i\) is the fitness function.
3 Application example

In this paper, for verifying the method of semi rigid connection modeling with rotational spring in SAP Ver. 11.07 program, a beam is exposed to uniform loading w, with connection characteristic parameters and initial stiffness $K_i$ (e.g. Figure 1) and definite section and load analyzed, then, the results (ultimate moment, $M_u$) have been compared with the results in Sultan Abdul Rassak. This comparison is shown in Table 1.

![Figure 1. Use rotational springs for semi rigid connection modelling](image)

Table 1- Results of modeling method for semi rigid connection.

<table>
<thead>
<tr>
<th>Analyze Method</th>
<th>Section</th>
<th>$I$ (in$^4$)</th>
<th>$K_i$ (k.in/rad)</th>
<th>$M_u$ (k.in)</th>
<th>$E$ (k.in$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sultan Abdul Rassak</td>
<td>W8x21</td>
<td>75.3</td>
<td>27795</td>
<td>406</td>
<td>29000</td>
</tr>
<tr>
<td>This paper</td>
<td>W8x21</td>
<td>75.3</td>
<td>27795</td>
<td>405.53</td>
<td>29000</td>
</tr>
</tbody>
</table>

3.1 Design of 9-story with three bays

The sizes of population, possibility of mutation, and maximum number of generations have been assumed to be equal to 30, 0.005 and 100, respectively. SAP2000 (Ver. 11.07) traditional engineering software has been used for modelling the frames, and coding in MATLAB software has been used for optimization procedure. The initial generation critically affected the convergence, the performance and the ability of the GA. If the size of design space is small, these properties of the GA may not be influenced.

There would be too much savings in optimum weights when the process continues until the end of the maximum iteration. The effectiveness of the story height and stiffness of connection on period of structure is not considerable.

In fact, by changing the connection of structure to semi-rigid connection, we decrease the frame and beam column connection stiffness and increase the alternation time of structure. Therefore, with the acceleration or force being fixed due to the decrease of frame hardness, the maximum and decreasing the stiffness of frame and beam column connection, the alternation time of structure to be increased. The aforesaid factors have a more effective role in the frame element design of frame will be affected by them. For this reason, to control the maximum displacement of the last story and relative displacement of the stories, we observe the need of more improvement of member and weight increase.

Table 2 Represents the results obtained from analysis of 9-story with three bays frame in the manner that in this frame the weight of structure in linear analysis state with rigid connection and in non-linear analysis state with semi-rigid connection reaches to maximum and minimum, respectively.
Table 2- Result of optimization for nine story steel frames

<table>
<thead>
<tr>
<th>TOPIC</th>
<th>Linear Static Analysis</th>
<th>Non-Linear Static Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rigid Connection</td>
<td>Semi-Rigid Connection</td>
</tr>
<tr>
<td>Weight (Kg)</td>
<td>18832.33</td>
<td>15940.69</td>
</tr>
<tr>
<td>Lateral Displacement Top Story (m)</td>
<td>0.0814</td>
<td>0.1794</td>
</tr>
<tr>
<td>Period (Sec)</td>
<td>1.4263</td>
<td>2.6893</td>
</tr>
<tr>
<td>Number of Analysis &amp; Design Process</td>
<td>25</td>
<td>2820</td>
</tr>
<tr>
<td>Number of Plastic Hinge</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

In non-linear analysis state with semi-rigid connection, the weight of structure is decreased compared more to other analyses (e.g. Figure 2).

![Figure 2. Design history of the three bays, nine stories](image)

There would be too much savings in optimum weights when the process continues until the end of the maximum iteration. The effectiveness of the story height and stiffness of connection on period of structure is not considerable.

4 Summary and conclusion

Considering the presented explanations and examples, it is observed that the application of genetic algorithm on analysis and design programs can change the procedure of analysis and design in the manner that there will be no need for the initial estimation of sections and control of stresses by the designers. Of course, the current initial estimation may reduce time of analysis. The analysis, design and selection of optimum sections will be performed by the program and the final design will be performed considering the proposed sections by the program and special executive issues of that project which will not take too much the time of the designer too much.

Considering the obtained results, tables and Figs, the proposed results are presented as follows:

- Considering the shear force, the average stiffens of connection in semi-rigid frames increase in each story downwardly until it has become close to the restraint border.
• In the frames analyzed with semi-rigid connection, the optimum stiffness of connection in linear analysis state is more than non-linear state.
• In the frame being studied is that the weight of structure in non-linear analysis method is generally less than the linear analysis method.
• Non-linear analysis method is more accurate than linear analysis method and in fact more percentage of elements capacity is used leading to decrease of consumed materials.

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