

# Structural Optimization Assessment for Steel Structures

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#### Abstract

For efficient analysis of steel structures, the actual responses of beam to column connections were analyzed in the present study. Even though idealized structural definition simplifies the analysis, predicted responses of the idealized structure may be quite unrealistic. Because of these unrealistic results, in the practice, most of the beamcolumn connections used in steel frames have semi-rigid deformation behavior. In addition, neglecting such behavior may lead to unrealistic predictions of the stiffness and strength of steel structures, and to less than optimal design in steel construction. Therefore, it is necessary to account of the effects of connection flexibility in the design.

The main purpose of this study is to define an optimization approach based on optimum criterion for the behavior of semi-rigid connections considering the importance of the behavior of connections in the practice of steel constructions. The optimization method accounts for both members and connections by taking member size and connection stiffness as design variables in the process. An optimization algorithm is applied to minimize the structural weight subject to constraints on stress and displacements under specified design loads. For this aim, optimal design stages of 3-10 and 20-story rigid and semi rigid connected frames are compared. The results of this study indicate that the proposed semi rigid steel frame optimization design method is much more appropriate design than the traditional one.

Keywords: Semi rigid connection; Optimal design; Steel structures

### Introduction

For analyzing the actual behavior of beam-column, connection is idealized as either rigid or pin. At rigid connections, displacement and slope continuity are fully transferred to bending moments. At pin connections, rotation continuity is non-existing with no bending moment transition. However, the predicted response of idealized structure may be quite unrealistic. This is because most connections used in current practice actually have semi-rigid behavior [1].

Recognizing the importance of the semi rigid behavior of connections, here, it has been aimed to understand the effect of the actual behavior of semi rigid connections. In the case of system stability, the constraints were defined associated with linear Eigen value problem. This definition of system stability for some structures may not be valid because of the nonlinear behavior of the structure which may be due to the geometry of the structure or the presence of geometric nonlinearity.

A well-defined procedure for these structures would be analyzing structure by using nonlinear equilibrium equations. This will be particularly good for structures with large span. In this paper, an optimization method based on optimality criterion approach is presented for structures with geometric nonlinear behavior. Nonlinear behavior of structures is determined by performing pushover and nonlinear dynamic time history analyses.

In this study, a realistic method for optimum design of steel structures that accounts for the behavior of semi rigid connections. The optimum design sought by method has the minimum weight of structures in the limit of stresses and displacements. Members are sized using standard steel sections. This optimization algorithm is applied for rigid and semi rigid connected three different structures. These structures are chosen as rigid and semi rigid connected 3, 10 and 20story.

The objective of this study is to define an optimal design approach for understanding steel construction behavior under static loading with semi rigid connections.

## **Design and Application**

To incorporate the behavior of semi-rigid connections into steel frame analysis, each beam to column connection is modeled as a rotational spring. The connection stiffness and member sizes are taken as continuous.

In the optimization methodology, constrains are defined as stresses and displacements according to the design codes. A continuous discrete optimization algorithm is employed to minimize the weight of the members of structure for the structure subject to constraints on stresses and displacements under static loading [2].

The members are sized using standard steel sections. For semi rigid connected frames, the effects of connection flexibility are modeled by attaching rotational springs as given in Figure 1.



Figure 1: Planar semi rigid member.



Additional connection elements can be modeled for beam-column connections. A semi-rigid connection is given in Figure 2.

In this study, each beam to column connections are modeled as a lengthwise rotational springs. Each element is comprised of a finitelength beam-column member with lengthwise rotational springs at the ends [3-5].

Design of Steel building frames has been based on simplifying assumptions concerning the behavior of beam to column connections. The main difficulty in performing semi-rigid frame design is in assessing the nonlinear behavior of the connections over the entire range of loading.

The process of accounting for nonlinear connection behavior in steel frame analysis and design is quite complicated comparing to others and requires the use of computer software [6,7].

In this study, the problem of optimum design of steel frame considering both semi rigid connection behavior and weight of members is formulated. The optimization algorithm is applied on rigid and semi rigid connected three different steel structures.

These structures are chosen as rigid and semi rigid connected 3, 10 and 20-story.

In Figure 3, Rigid connected frames are shown. In Figure 4, semi rigid connected frames are shown, used in the analyses. The connection behavior has influence on the response of the structure and considerable effects on the weight of the members of structure. Each

structural member is to be sized using a standard steel section and as such its cross section area is a variable to the design.

The design optimization process is repeated until converge occurs for successive design stages at which point the minimum design has been found [8]. In the nonlinear structural analysis, it is accounted for the semi-rigid behavior of the selected connections is conducted to evaluate the structural responses for final design.

The results of this process are given in Figure 5. In Figure 5, calculated members weights are given with the change of design stage. It is obvious that semi rigid connection is much more optimal compared with the rigid one.



Figure 3: Rigid Connected 3-10 and 20-story steel structures.







# **Figure 5:** Member weight comparison of rigid and semi rigid connected 3-10 and 20-story steel structures.

# Nonlinear Static Pushover Analysis

The pushover analysis can be described as applying lateral loads in patterns that represent approximately the relative inertial forces generated at each floor level and pushing the structure under lateral loads to displacements that are larger than the maximum displacements expected in design earthquakes [9]. The pushover analysis provides a shear vs. displacement relationship and indicates the inelastic limit as well as lateral load capacity of the structure. The changes in slope of this curve give an indication of yielding of various structural elements. The main aim of the pushover analysis is to determine member forces and global and local deformation capacity of a structure. The information can be used to assess the integrity of the structure.

After designing and detailing the steel frame structures, a nonlinear pushover analysis is carried out for evaluating the structural seismic response. For this purpose the computer program Drain 2D has been used. The simplified loading pattern is chosen as triangular (IBC, k=1), where k is an exponent related to the structure period to define vertical distribution factor. This is used in the nonlinear static pushover analysis of 3, 10, and 20-story steel frame structures [10]. In addition to the lateral loadings, frames are subjected live loads and dead weights. The lateral force is increased for 3, 10-story steel frame structures until the roof displacement reached 50 cm and 100 cm for 20-story frame structure. Beam and column elements are used to analyze the frames. Inelastic effects are assigned to plastic hinges at member ends. Strain-hardening is neglected in all elements. Bilinear moment-rotation relationship is assumed for both beam and column members.

The results of the pushover analyses are presented in Figures 6-8. The pushover curves are shown for the triangular distribution, for each frame structures. The curves represent base shear-weight ratio versus story level displacements. Shear V was calculated by summing all applied lateral loads above the ground level, and the weight of the building W is the summation of the weights of all floors. Beside, these curves represent the loss of lateral load resisting capacity and shear failures of a column at the displacement level. The changes in slope of these curves give an indication of yielding of various structural elements, first yielding of beam, first yielding of column and shear failure in the members. By the increase in the height of the frame structures, first yielding and shear failure of the columns is experienced at a larger roof displacement (Figures 6-8.)



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### Conclusion

Connection behavior may significantly affect the global behavior of a structure. The lateral drift of structures is substantially increased by semi rigid connection behavior. Semi rigid connection is much more suitable comparing to the rigid ones because rigid connection has unrealistic behavior. The moments in beams and the moments in columns may be over-estimated and under estimated respectively. This may lead to heavier design than it is supposed to be. In fact, rigid connection is unrealistic and their realistic stiffness is often in the range of 80% or 90% of rigid connection. If this connection is considered the rigid connection, the members in the structure are over stressed and predictions of drift cannot be predicted accurately.

Semi rigid design comes into its own for low and mid-rise structures when gravity loads control the design and sway is relatively unimportant. Here, member weights are optimal and lower than those comparable to the rigid ones. In this study, the optimal design stages for steel constructions considering the minimum weight of members with semi-rigid and rigid connections were compared. In Figure 5, member weight comparison of rigid and semi rigid connected in 3-10 and 20-story steel constructions are given. As seen in Figure 5, the semi-rigid connection has a significant effect on member weight and in the optimal design. As given in Figure 5, it is seen, at the first stage, the weight of semi-rigid connected structures are decreasing approximately 20% compared with rigid connection. This presentation is changing between 10% to 25% and in the  $2^{nd}$  and  $3^{rd}$  stages.

In Figures 6-8, push over curves for rigid and semi rigid connected structures for each steps were given. It is aimed to summarize the effects of semi rigid connection and optimal design in the Figures to the behavior of the steel structures. Push over curves for the  $2^{nd}$  and  $3^{rd}$  stages, are close to each other. Therefore, the optimal design after  $3^{rd}$  stage is proved.

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