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Direct displacement-based seismic design of semi-rigid steel frames

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A B S T R A C T

Semi-rigid steel frames are often considered a cost-effective alternative to conventional fully rigid steel frames, because they use the economical partially restrained (PR) connections instead of the costly moment connections while performing satisfactorily under seismic loads. So far, semi-rigid steel frames have typically been designed using the traditional force-based method that is meant for the design of fully rigid steel frames. With this method, the sizing of various structural components is firstly carried out per code strength requirements and then revised iteratively to satisfy the stiffness requirements on both individual structural components and the overall frame. As a result, a designer often encounters considerable difficulty in achieving a structural solution that meets the target displacement and attains a desired yield mechanism. To address this issue, we propose a facile displacement-based method for the seismic design of semi-rigid steel frame structures by directly and explicitly relating the target displacement and deformation to the appropriate sizing of various structural components in terms of their strength, stiffness, and ductility. The new method is based on a simplified analytical semi-rigid frame model assuming that the structural plastic deformation is mainly concentrated within the PR connections while beams and columns largely remain elastic. A step-by-step procedure for implementing the new method is described and illustrated with example semi-rigid steel frame designs. The usefulness of the new method is demonstrated by comparing the target displacement and deformation values specified as a design objective with the actual values predicted by a nonlinear static pushover analysis.

1. Introduction

In a semi-rigid frame, beams and columns are connected by partially restrained (PR) connections [1], which typically have a moment-resisting capacity less than that of the connected beam and possess a flexural rigidity between those of a simple connection and a fully rigid connection. Numerous experimental and numerical studies have clearly demonstrated that the seismic performance of semi-rigid frames is comparable to that of fully rigid frames [2–8]. More important, semi-rigid frames have a number of seismic advantages. First, PR connections exhibit a satisfactory ductile behavior. For example, the bolted PR connections show a favorable energy-dissipating hysteresis through the inelastic structural deformation and slippage between the contacting surfaces, thereby eliminating the potential brittle fracture of welded components [6]. Second, the reduction of beam-end strength by PR connections makes it easier to use lighter column members to comply with the strong-column–weak-beam requirement [2]. Third, because beams in a semi-rigid frame remain almost elastic, the stringent seismic compactness requirement for beam sections may be lifted, thus enabling more freedom in sizing such structural members. Indeed, the above salient advantages make semi-rigid frames an economic alternative to conventional fully rigid frames in seismic applications.

So far, however, no methods have been specifically developed for the seismic design of semi-rigid frames. As a result, the traditional force-based method has to be used as a temporary means, causing at least two major issues. First, it is not straightforward to determine the required strength and stiffness of PR connections such that they can seismically perform with the connected beams and columns in the most cost-effective manner. Hence, prior experience in designing semi-rigid frames is very much needed and multiple iterations may be necessary to reach a final design solution. Second, the target displacement and acceptable deformation level are not directly considered when sizing the individual components of a semi-rigid frame. This is because the structural strength requirement is usually satisfied first and then the structural stiffness is evaluated as a secondary step. Hence, it is both challenging and inconvenient to design a semi-rigid frame to satisfactorily meet the target displacement requirement and attain a desirable plastic deformation mechanism. To resolve these issues, new methods are urgently needed to streamline and expedite the process of sizing the PR connections and structural members of a semi-rigid frame so that the target displacement and favorable deformation pattern can be met directly and rapidly in the design process.

The displacement-based seismic design methodology has been developed in recent years trying to overcome some of the significant drawbacks associated with the traditional force-based design method [9–12]. Using a displacement-based method, a designer is able to explicitly express the requirements on the strength, stiffness, and ductility of

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structural components in terms of the target displacement and deformation pattern. The plastic design concept is adopted to ensure that the structure attains a pre-defined ductile mechanism under the design seismic loads [13]. In order to evaluate the actual seismic performance of a thus designed structure, nonlinear static pushover analysis, a relatively simple and computationally economical numerical technique, is often used in lieu of the highly accurate albeit very expensive nonlinear time-history analysis [14–16].

In this paper, we propose a facile method for the direct displacement-based seismic design of semi-rigid frames. This method is derived by using a simplified analytical semi-rigid frame model and assuming a reasonable plastic deformation mechanism. The target displacement is successfully converted to the demands on the rotational capacities of PR connections, based on which the sizing of beams and columns is carried out subsequently. A step-by-step design procedure for implementing the new displacement-based method is described in detail and illustrated with two design examples. The usefulness of the new method is critically assessed by comparing the specified target displacement and deformation values with the actual values calculated by pushover analysis.

2. Displacement-based seismic design method

The step-by-step procedure that implements the direct displacement-based design method is briefly described as follows. First, the design lateral seismic forces are calculated based on the target displacement, using a capacity design concept commonly adopted in the performance-based earthquake engineering [14]. Then, the capacities of PR connections are determined to ensure that the semi-rigid frame reaches the target displacement with a pre-defined yield mechanism. After that, beams are designed to have an optimal level of strength and stiffness relative to those of PR connections. Finally, columns are sized to resist the combined moment and axial forces resulting from both gravity loads and PR connection reactions. The above major steps for the displacement-based design of semi-rigid frames are presented in detail in the next sections.

2.1. Calculation of seismic forces based on target displacement

In order to determine the design seismic forces associated with the target displacement (usually specified at the roof level), the acceleration-displacement response spectrum (ADRS) method provided in ATC 40 [14] is used to calculate the total base shear at the ultimate level. This method is briefly described as follows.

First, the 5%-damped elastic design response spectrum Sa is reduced to reflect the dissipation of seismic input energy through inelastic structural deformation. The reduction factor is a function of ξ_{eff}, the effective damping ratio of an inelastic structure obtained from its force-displacement curve. For steel frames with bolted PR connections, ξ_{eff} typically varies between 0.1 and 0.15 [9,17]. Given a value of ξ_{eff}, the linear and curved portions of the elastic spectrum are reduced by the following two factors, respectively:

$$SR_A = \frac{3.21 - 0.68\ \ln\left(\xi_{eff}\right)}{2.12} \quad (1)$$

$$SR_V = \frac{2.31 - 0.41\ \ln\left(\xi_{eff}\right)}{1.65} \quad (2)$$

The reduced spectrum is then converted to the ADRS format by

$$Sd_j = \frac{T_j^2}{4\pi^2} Sa_j \cdot g \quad (3)$$

where T_j is the jth vibrational period and g is the gravitational acceleration. The target roof displacement at the ultimate level, Δ_u, is converted to the target spectral displacement Sd_u by

$$Sd_u = \Delta_u \left[\sum_{i=1}^{n} \left(m_i \varphi_{i1}^2\right)\right] / \left[\varphi_{n1} \sum_{i=1}^{n} \left(m_i \varphi_{i1}\right)\right] \quad (4)$$

where φ_{i1} is the ith-story amplitude of the fundamental mode of vibration, n is the number of stories, and m_i is the seismic mass of the ith story.

The target spectral acceleration Sa_u that corresponds to Sd_u on the reduced ADRS curve is used to calculate the ultimate-level total base shear as

$$V_b = \alpha_1 W \cdot Sa_u \quad (5)$$

where W is the total seismic weight and α_1 is the first modal mass coefficient calculated as

$$\alpha_1 = \left[\sum_{i=1}^{n} \left(m_i \varphi_{i1}\right)\right]^2 / \left[\left(\sum_{i=1}^{n} m_i\right)\left(\sum_{i=1}^{n} \left(m_i \varphi_{i1}^2\right)\right)\right] \quad (6)$$

The total base shear at the service level, V_s, can then be selected by a designer to be an appropriate fraction of the total base shear at the ultimate level. That is,

$$V_s = \gamma V_u \quad (7)$$

where γ can be reasonably taken as, for example, 0.6. Besides, the roof displacement at the service level, Δ_s, is decided as 0.8% of the building height. Therefore, the total base shear vs. roof displacement curve, as desired by a designer, is completely established (Fig. 1).

Finally, the total base shear V (V_s or V_u) is distributed over the building height by using, for example, the ASCE 7 formula [18]:

$$F_i = \left(w_i h_i^k / \sum_{i=1}^{n} w_i h_i^k\right) V \quad (8)$$

where F_i, w_i, and h_i denote the lateral seismic force, seismic weight, and height, respectively, of the ith story of the frame, and k is a distribution exponent related to the fundamental period of the structure [18].

2.2. Development of a simplified semi-rigid frame model

At any joint of a semi-rigid frame, the overall flexural stiffness of the subassembly, which includes a story beam and its end PR connections that are linked in series to the supporting column, is small compared to that of the column. As a result, it is reasonable to expect that the lateral deformation of a semi-rigid frame is primarily contributed by the elastic/plastic rotation of its PR connections and elastic deformation of

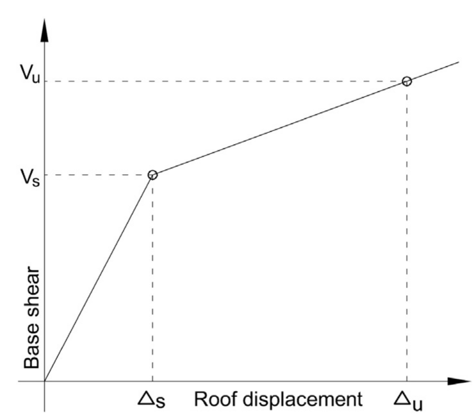

Fig. 1. The base shear vs. roof displacement curve of a semi-rigid frame.