Journal of Constructional Steel Research 88 (2013) 15–20

Contents lists available at SciVerse ScienceDirect

Journal of Constructional Steel Research

# Probabilistic assessment of connections for steel buildings on seismic zones

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ARTICLE INFO

*Article history:*
Received 15 August 2012
Accepted 8 April 2013
Available online 28 May 2013

*Keywords:*
Bolted and welded connections
Seismic response
Life-cycle expected cost
Seismic risk

ABSTRACT

The findings about the fragile behavior of steel welded connections after the Northridge 1994 earthquake, specially for frames designed to withstand lateral force, have brought an amount of new attention to the design and safety issues of the welded connections for structures located on seismic zones. In México, practitioners and designers are wondering about the seismic effectiveness of the several kinds of connections as used in steel structures.

A decision must be made to balance the safety required with the costs incurred after exceeding the serviceability limit state. Structural reliability techniques provide the proper framework to include the inherent uncertainties into the design process.

Registered motions after the 1985 Mexico City earthquake are properly scaled according to the seismic hazard curve for soft soil in Mexico City. Earthquake occurrence is modeled as a Poisson process and the expected life-cycle cost is taken as the decision criteria.

Parametric analyses allow the identification of dominant variables and ranges where one option is more recommendable than the other one.

The proposed formulation may support designers and builders for the decision making process about the selection of the convenient connection type for the seismic zones with soft soil in Mexico City.



## Introduction

Steel buildings are a common design solution for seismic zones. However, the selection of the appropriate connection type is still an issue in Mexico. Special interest has been raised about the fragile behavior of welded connections, especially after the amount of damages experienced due to the Northridge earthquake [1] that occurred in California in 1994. The SAC Project [2], developed in the US under FEMA's coordination, provided some insight to improve the understanding of the seismic behavior of welded connections [3,4]. In Mexico, some efforts have been made to derive practical recommendations for steel connections [5–8]. Alternate loading is an important factor to produce cumulative damage [9] and, recently, the fracture mechanism of typical connections has been studied under the light of reliability analyses [10].

Usually the collapse limit state is emphasized to provide design recommendations [11,12] but, given the character and extension of the damage produced by some earthquakes and the time the structure is off-service during repairs, the serviceability condition is also a concern. Structural reliability and life-cycle costing [13] serve as the measuring tools to weigh the cost/benefit relevance of the various connection alternatives and to balance the trade-off between required safety and costs of the damage consequences.

A seismic hazard curve, previously developed for Mexico City [14] is used with scaling factors to assess the seismic vulnerability of the structures.

Given that the connection forces due to the seismic environment are uncertain, statistics of the maximum acceleration demands are obtained at the connection location for a typical building through Monte Carlo simulation and, with these statistics and the connection model, statistics of the maximum responses are obtained. Maximum moment and maximum shear force histograms are obtained with these statistics and, using the limit state function appropriate for the given connection type, probabilities of failure and damage are obtained for both demand levels: extreme and operational earthquakes. These probabilities are introduced into the life-cycle cost/benefit relationship for several connection types and the optimal type is obtained by comparing the expected life-cycle costs. The minimum expected life-cycle cost corresponds to the optimal connection type. Damage costs include the repair cost and losses related to the potential fatalities, injuries and business interruption. The results may also be used, after further refinements, to update the design specifications for seismic zones in Mexico.

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http://dx.doi.org/10.1016/j.jcsr.2013.04.003

## Formulation of the decision criteria

The expected life-cycle cost is usually calculated to assess the economic effectiveness of potential structural solutions and come up to optimal decisions under uncertain loading conditions [15,16]. In this paper, two alternative connection types are proposed and their performances are compared from the viewpoints of structural reliability and costs. The expected life-cycle cost $E[C_T]$ is composed by the initial cost $C_i$ and the expected damage costs $E[C_D]$:

$$E[C_T] = C_i + E[C_D]. \quad (1)$$

The expected damage costs include the components of damage cost: expected repair $E[C_r]$, injury $E[C_{inj}]$ and fatality $E[C_{fat}]$ costs and each one depends on the probabilities of damage and failure of the structure. These component costs of damage are defined as:

$$E[C_r] = C_r(PVF)P_r \quad (2)$$

Where $C_r$ = average repair cost, which includes the business interruption loss, $C_{bi}$. The average repair cost includes the material repairs and loss due to business interruption while the repair works are performed. $PVF$ = present value function [16].

$$PVF = \sum_{n=1}^{\infty}\left[\sum_{k=1}^{n}\Gamma(k,\gamma L)/\Gamma(k,\nu L)(\nu/\gamma)^k\right](\nu L)^n/n!\exp(-\nu L) \quad (3)$$

where $\nu$ = mean occurrence rate of earthquakes that may damage the structure, $\gamma$ = net annual discount rate, and $L$ = structure life. Also, $P_r$ = probability of repair, defined in a simplified way, as the probability to reach the allowable limit state, which is in terms of the allowable stress for either the bolted or the welded connection.

Similarly, the business interruption cost, $C_{bi}$, is expressed in terms of the loss of revenue due to the repairs or reconstruction works after the earthquake, assumed to last $T$ years:

$$C_{bi} = L_R(T) \quad (4)$$

where $L_R$ = loss of revenues per year. The expected cost of injuries is proposed to be:

$$E\left[C_{inj}\right] = C_{IL}(N_{in})P_f \quad (5)$$

where $C_{1I}$ = average injury cost for an individual, $N_{in}$ = average number of injuries on a typical steel building in Mexico given an earthquake with a mean occurrence rate $\nu$ and $P_f$ is the annual failure probability.

For the expected cost related to loss of human lives, the cost corresponding to a life loss, $C_{1L}$, and the expected number of fatalities, $N_D$ are considered. The cost associated with a life loss may be estimated in terms of the human capital approach, which consists in the calculation of the contribution lost, due to the death of an individual, to the Gross Domestic Product during his expected remaining life. The details of this calculation are explained in previous works [13]. The expected number of fatalities is estimated from a curve previously developed for typical buildings in Mexico, in terms of their plan areas, given an earthquake with a mean occurrence rate $\nu$ [13]

$$E\left[C_{fat}\right] = C_{1L}(N_D)P_f. \quad (6)$$

In the next section, all the figures are estimated for typical costs in USD for Mexico.

A typical geometry of a building frame, see Fig. 1, located on the soft soil of Mexico City is selected to analyze its critical frame under seismic loads. A series of conventional "push-over" analyses were performed to identify the critical frame responses. Statistics of the frame maximum response, at critical joint level, are obtained from the frame analyses subjected to Poissonian earthquakes (with mean occurrence rate $\nu$) as scaled from the seismic hazard curve for Mexico City [14]. The soft soil conditions of Mexico City are already included in the seismic hazard curve, because the seismic failure rates from [14], come from frames built on the soft soil of Mexico City. The intensities exceedance rate is obtained from this reference, then the annual cumulative distribution of intensities and the average exceedance rate are calculated and, finally, with the assumption of Poissonian occurrence [17], the annual cumulative probability of seismic intensities is obtained.

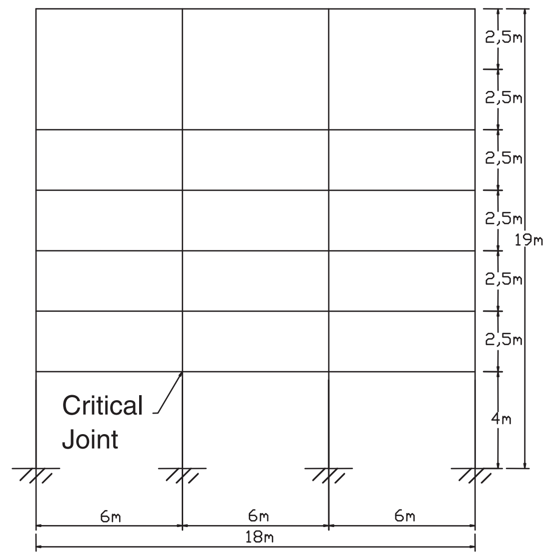


**Fig. 1.** Typical frame for a steel building in Mexico.

The annual cumulative probability of intensities in the soft soil of Mexico City is obtained from the above mentioned seismic hazard curve. This is calculated by using $P = \exp(-\nu T)$ for $T = 1$ year (earthquake occurrence according to a Poisson process for a 1 year period) and, with the mean exceedance rate of intensities $\nu$ obtained from [14] (see Fig. 2).

The above described response statistics are used as an input to the FEM models of the alternative connections and a Monte Carlo simulation process [18] is performed for each connection model in order to get the statistics of maximum shear force and moment. With these statistics and the limit state function of each connection, the corresponding failure probabilities are calculated. In the FEM analyses, the plastic hinge is identified once the plastic moment ($Mp = ZFy$) is reached by the acting moment at the columns ends. Also, the failure

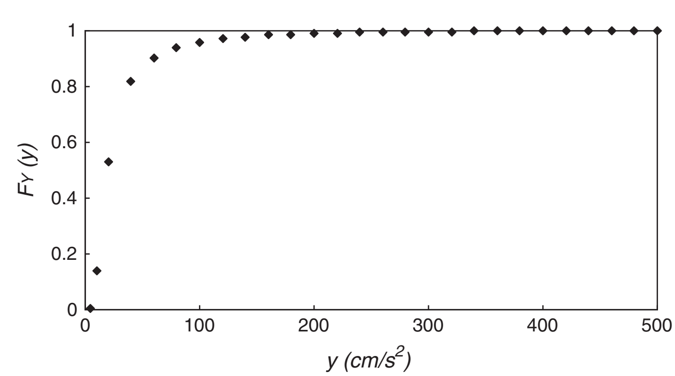


**Fig. 2.** Cumulative annual probability of seismic intensities.