RELIABILITY-BASED DECISION MAKING FOR STEEL CONNECTIONS ON SEISMIC ZONES

David De Leon(1)

ABSTRACT

The findings about the fragile behavior of steel welded connections after the Northridge 1994 earthquake, specially for frames designed to withstand lateral force, has 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 costs are expressed as a function of the damage level.

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.

KEY WORDS

Steel connections, reliability, life-cycle costing, decision making, seismic design.

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, especially after the amount of damages experienced due to the Northridge earthquake (Bruneau, et al., 1998) occurred in California in 1994. The SAC Project (SAC project, 1994), developed in the US under FEMA´s coordination, provides some insight to improve the understanding of the seismic behavior of welded connections.

Usually the collapse limit state is emphasized to provide design recommendations 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 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.

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[1] Professor, Engrg. Department, Ciudad Universitaria, Toluca, México, Univ. Aut. del Estado de México, 50130, México, Phone (52) 722/2140855 Ext. 259, FAX (52) 722/2140855 Ext. 110, dleon@uaemex.mx

A seismic hazard curve, previously developed for Mexico City (Esteva and Ruiz, 1989) is used with scaling factors to assess the seismic vulnerability of the structures.

Throughout Monte Carlo simulation, statistics of the maximum acceleration demands are obtained at the connection location for typical buildings and, with these statistics and the connection model, statistics of the maximum responses are obtained. With these statistics and the state limit function, for a 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 value 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.

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 (Neves, Frangopol and Hogg, 2003; Ang and De León, 2005).

Two alternative connection types are proposed and their performances are compared under the viewpoints of structural reliability and costs.

The expected life-cycle cost $E[C_L]$ is composed by the initial cost C_i and the expected damage costs $E[C_D]$:

$$E[C_L] = C_i + E[C_D] \tag{1}$$

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:

$$E[C_r] = C_r (PVF) P_r \tag{2}$$

where:

C_r = average repair cost, which includes the business interruption loss, $C_{bi,}$

PVF = present value function (Ang and De León, 2005).

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

where ν = mean occurrence rate of earthquakes that may damage the structure, γ = net annual discount rate, and L= structure life.

And P_r = probability of repair, defined in a simplified way, as a factor of the failure probability.

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:

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

where:

L_R = loss of revenues per year

The expected cost of injuries is proposed to be:

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

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 ν.

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 (Ang and De León, 1997). 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 ν.

$$E[C_L] = C_{1L}(N_D)P_f \tag{6}$$

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

A typical geometry of a building, see Fig. 1, located on the soft soil of Mexico City is selected to analyze its critical frame under seismic loads. Statistics of its maximum response, at critical joint level, are obtained from the frame analyses subjected to Poissonian earthquakes (with mean occurrence rate ν) as scaled from the seismic hazard curve for Mexico City (Esteva and Ruiz, 1989).

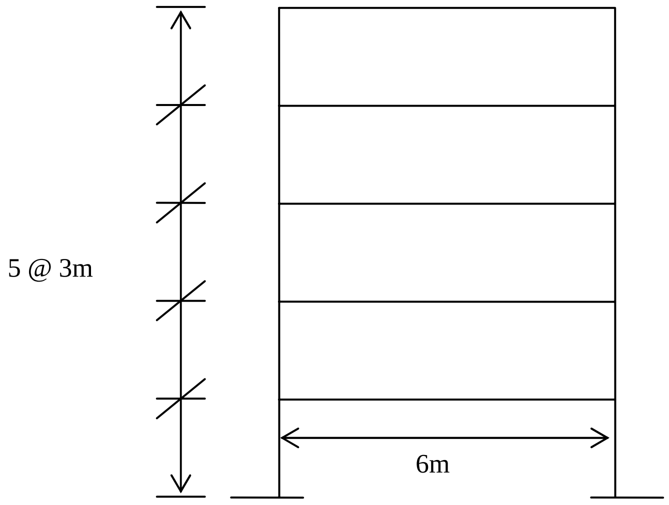


Fig. 1 Typical frame for a steel building in Mexico

The above described response statistics are used as an input to the FEM models of the alternative connections and a Monte Carlo simulation process 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. As an example, g_1 and g_2 are the state limit functions for maximum moment and for each one of the two alternative connections.

$$g_1 = 5.39 - M_1 \tag{7}$$

$$g_2 = 3.38 - M_2 \tag{8}$$

where M_1 and M_2 are the maximum moments for the alternative connections.
With the calculated failure probabilities, and Eqs. (1) to (6), the expected life-cycle cost of each connection is obtained. The connection type to be recommended is the one with the minimum life-cycle cost.

APPLICATION TO A STEEL BUILDING IN MEXICO

The calculation process described in the last section is performed to the frame shown in Fig. 1 and the statistics of seismic spectral information is shown in Table 1. The mean $E[C_S]$ and coefficient of variation CV_{Cs} of the seismic coefficient are considered to generate random seismic excitations.

Table 1. Seismic information for Mexico City

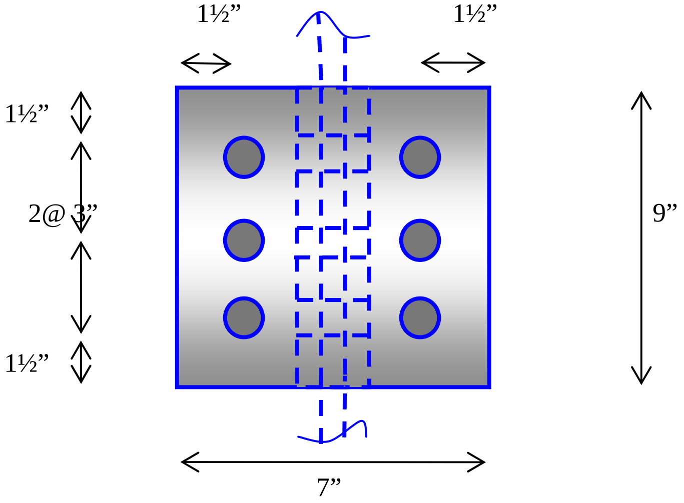
$E[C_S]$ =	0.45
CV_{Cs} =	0.3
ν =	0.142

The critical joints were found to be the first floor connections.
The costs data are shown in Table 2.

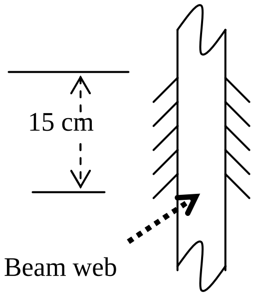
Table 2. Costs data (pesos)

C_i	10000
C_r	8000
γ	0.142
L_R	20000
C_{1i}	10000
C_{1L}	80000
N_{in}	0
N_D	60
L	50 years

The first proposed connection is a bolted joint with 2 angles and A325 7/8” bolts. The angles join the beam web with the column flanges. The second one is a welded set of 2 fillets with 15cm length and ¼” thickness with electrodes E70 to join the beam web to the column flanges. A general view of the alternative connections is shown in Fig. 2.



(a) Front view of bolted connection



(b) Front view of welded connection

Fig. 2 Alternative connections (a) bolted, (b) welded

The distribution of the critical forces at the joints, for the alternative connections, are shown in Figs. 3 and 4.

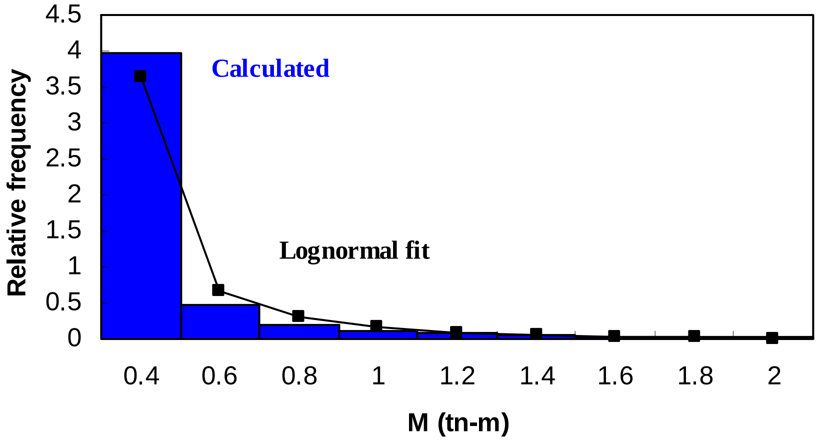


Fig. 3 Distribution of maximum moments at critical joint

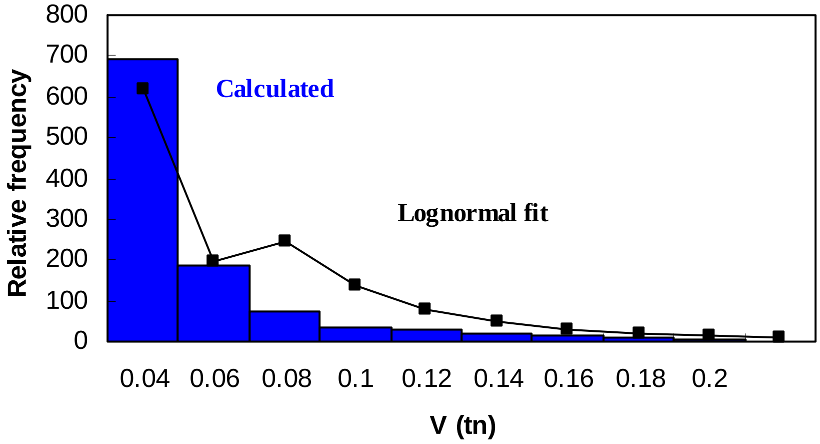


Fig. 4 Distribution of maximum shear forces at critical joint

The bending mode was found to govern the connection failure. A sample of the simulation process is shown in Table 3.

Table 3. Repair and failure probabilities for alternative connections

Random number uniform	Random number LN	M_1 (tn-m)	g_1	g_2
0.0044	-2.617	0.024	0	0
0.4713	-0.071	0.222	0	0
0.5094	0.023	0.242	0	0

ξ_M=	0.863
λ_M=	-1.438

The repair and failure probabilities, for the alternative connections, are shown in Table 4.

Table 4. Repair and failure probabilities for alternative connections

$Pr_{1\,M}$	$Pr_{2\,M}$
0.069	0.004
$Pf_{1\,M}$	$Pf_{2\,M}$
0.001	0.001

With the above obtained failure probabilities, the expected life-cycle costs are calculated and the results are shown in Table 5.

Table 5 Expected life-cycle costs for alternative connections

Alternative	$E[C_r]$	$E[C_{fat}]$	$E[C_{inj}]$	C_i	$E[C_D]$	$E[C_T]$
1	14490	96096	0	10000	110586	120586
2	840	96096	0	10000	96936	106936

DISCUSSION OF RESULTS

From the results obtained in the previous section, it is observed that the optimal connection type is the second one, the welded connection from beam web to column flanges.

The bending effect is the one that governs the connection design for the case treated here and for the seismic conditions illustrated.

Regarding the costs, the only difference between the two alternatives was the repair cost. This is due to the fact that the repair probability is different for these cases; it is more probable the repair for the bolted connection, where part of the work is made onsite, than the welded one which makes use of a more qualified workmanship.

Two simple options were included here for exemplification purposes. The decision tool may be extended to compare a wide variety of connections and details where the cost-benefit analysis is justified.

The results are useful for the hazard and site considered. Other conditions require an adaptation of data like, hazard type, seismicity and costs.

CONCLUSIONS AND RECOMMENDATIONS

A risk-based decision tool has been presented to select potentially feasible connection types in a steel building under seismic loads.

For the case considered here, a welded connection is preferred, from the cost effectiveness point of view, over a bolted one.

Further research may lead to a wider range of applications in order to compare design, construction and retrofit alternative schemes.

Also, with additional work, the criteria may be used to update the Mexican code for design and retrofit specifications.

ACKNOWLEDGEMENTS

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