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Probabilistic assessment of the structural safety of a type of bolted and welded connections for seismic zones

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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 facing the problem of the seismic effectiveness of the several kinds of connections as currently proposed for the design of 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 on the analyses and justification process towards the selection of the convenient connection type for the seismic zones with soft soil in Mexico City.

Key words: bolted and welded connections, seismic response, life-cycle expected cost, seismic risk.

Evaluación probabilista de la seguridad estructural de un tipo de conexiones atornilladas y soldadas para zonas sísmicas

Resumen

Los hallazgos del comportamiento frágil de conexiones soldadas de acero después del temblor de Northridge de 1994, especialmente para marcos diseñados para resistir cargas laterales, ha traído la atención en los aspectos de seguridad y diseño de conexiones soldadas para estructuras localizadas en zonas sísmicas. En México, ingenieros de la práctica y diseñadores se están preguntando cuál será la efectividad sísmica de varias alternativas de conexiones utilizadas en estructuras de acero. Se deben tomar decisiones para equilibrar el nivel requerido de seguridad con los costos en que se incurre cuando se excede un estado límite. Las técnicas de confiabilidad estructural proveen del marco adecuado para incluir explícitamente las incertidumbres inherentes al proceso de diseño. Movimientos del terreno registrados en el temblor de la Ciudad de México de 1985 se escalan apropiadamente de acuerdo a la curva de riesgo sísmico de la zona de suelo blando de México, DF. La ocurrencia de temblores se modela de acuerdo a un proceso de Poisson y se toma como criterio de decisión el costo esperado en el ciclo de vida. El análisis paramétrico permite la identificación de variables dominantes y se identifican rangos en los que una opción, de las conexiones propuestas, es más recomendable que la otra. La formulación propuesta puede apoyar a diseñadores y constructores en el proceso de toma de decisiones acerca de la selección del tipo conveniente de conexión para zonas sísmicas como la Ciudad de México.

Palabras clave: conexiones atornilladas y soldadas, respuesta sísmica, costo esperado en el ciclo de vida, riesgo sísmico.

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] 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 the uncertain nature of the forces at the connection, as a consequence that the seismic environment is also uncertain, responses to scenario spectral acceleration demands are obtained, at the connection location, for the typical building considered here. These responses are calculated throughout a Monte Carlo simulation process under scenario spectral accelerations. The Monte Carlo simulation process, the scenario accelerations, the response statistics and the connection models, are detailed ahead in the following sections. Maximum moment and maximum shear forces histograms are obtained with these statistics and, by using the appropriate limit state function 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 appropriate limit state function will correspond to whether the maximum moment exceeds its corresponding resistance or the maximum shear force exceeds its resisting force. 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 [15, 16]. 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 $E[C_D]$:

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

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}. 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]

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

where *k* is the number of earthquakes and *n* the number of earthquakes considered in the *nth*.-term composing the function in order to consider any number of earthquakes with Poissonian occurrence probability. Also, ν = mean occurrence rate of earthquakes that may damage the structure, γ = net annual discount rate, *L*= structure life and P_r = probability of repair, defined in a simplified way, as a 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:

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

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

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

where C_{IL} = 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 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 expected age of the individual, assumed to die during the earthquake, is simulated from the probabilistic distribution of ages for the population of Mexico City, as obtained from national statistics, and the estimated distribution of building occupants (with varying ages) at the time of the earthquake. The remaining life is estimated as the difference between the average life expectancy for Mexico City and this expected age. More details of this calculation are given in a previous work [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 ν [13].

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

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

A typical building frame, see Figure 1, located on the soft soil of Mexico City is selected to analyze its critical frame under seismic loads. A series of response analyses were performed to identify the maximum moments and shear forces under scenario spectral accelerations. Earthquakes are assumed to occur according to a Poisson processes (with mean occurrence rate ν), with spectral accelerations which are scaled from the seismic hazard curve for Mexico City [14]. From the accelerations exceedance rate found in this reference, it is obtained the annual cumulative distribution of spectral accelerations for the soft soil of Mexico City (see Figure 2).

The above described response statistics are used as an input to the (Finite Element Method) 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. As an example, $g_M{}^1$ and $g_M{}^2$ are the limit state functions for maximum moment and for each one of the two alternative connections.

$$g_M{}^1 = M_r{}^1 - M_1 \tag{7}$$

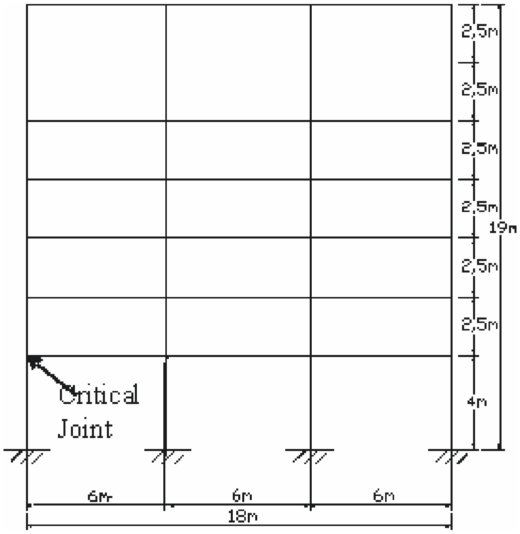

Figure 1. Typical frame for a steel building in Mexico.

$$g_M{}^2 = M_r{}^2 - M_2 \qquad (8)$$

where M_1 and M_2 are the maximum moments and M_r^1 and M_r^2 the resisting moments for the alternative connections 1 and 2, respectively. The corresponding functions for shear force and for the repair probability level are similar. The expected life-cycle cost of each connection is obtained through the calculated failure probabilities, and Eqs. (1) to (6). The connection type to be recommended will be the one with the minimum life-cycle cost.

Application to a steel building in Mexico

The plan of the considered building is shown in Figure 3 and the building belongs to group B,

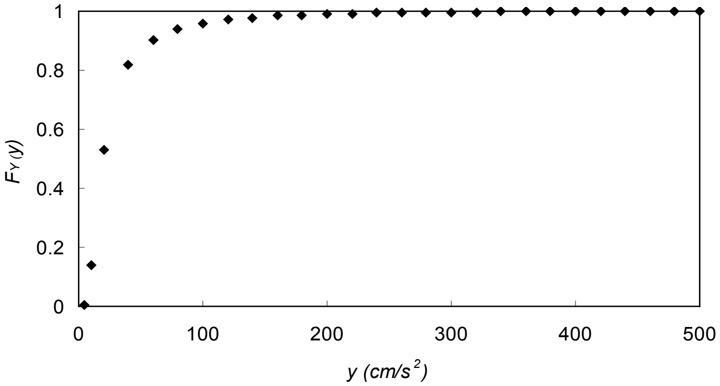

Figure 2. Cumulative annual probability of seismic spectral accelerations.

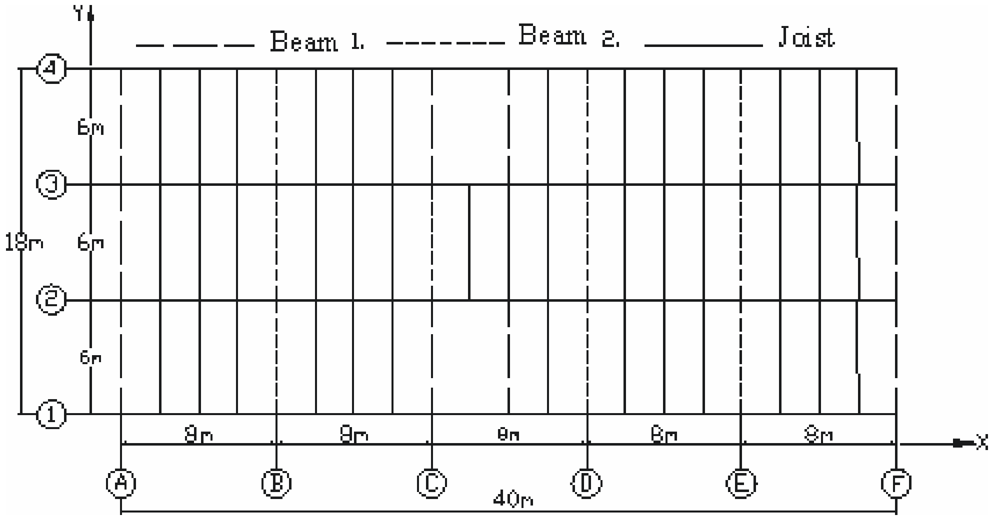

Figure 3. Plan of analized building.

according to the Mexico City building code [11]. The building is a regular, framed structure without bracings and the study is made with fixed cross sections, there is no parametric study with variable cross sections. The use of the bulding is for hotel rooms and the structure natural period is 0.58 s. The cross sections of beam and column at critical joint are: section W14X90 and box section 16“X16“X1/2“, respectively.

The joint is designed for two options: bolted (connection 1) and welded (connection 2). The bolted option is shown in Figure 4 whereas the welded connection is sketched in Figure 5.

The welded connection only consists on 15 cm filets on both sides of the web. The only joint considered was the edge one. The second alternative connection 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.

The designs were made to meet standard practices and assuming the application of conventional construction procedures. The annual mean occurrence rate of “significant” earthquakes is 0.142/year. “Significant” are considered to be those events that might produce enough damage in the considered building (corresponding to intensities larger than 0.15g).

In order to simplify the Monte Carlo simulation process, a series of preliminary structural response analyses were performed for specified spectral acceleration coefficients corresponding to the spectral accelerations given in the X-coordinates of the curve in Figure 2. The whole range of scenario spectral accelerations was divided into 4 parts: 0 to 0.15g, 0.15g to 0.25g, 0.25g to 0.35g and 0.35g to 0.45g and the maximum moment and maximum shear force were identified for each of the 4 limits. In all cases the critical joints were found to be the first floor connections. These maximum responses were fitted to nonlinear piecewise deterministic functions. Many trials were performed by randomly generating spectral accelerations (Figure 2) and by calculating the ratio between this acceleration and the closest limit. The maximum moment and shear force are estimated by multiplying the maximum moment and shear force observed for that limit, times the ratio between accelerations. The “pdf” (probability density function) of these maximums is calculated by conventional statistics and shifted gamma distributions [17] were fitted to the calculated maximum forces (see Figures 6 and 7). The repair and failure probability of both connections are calculated through the area under the curves. The repair limit states were considered on the basis to

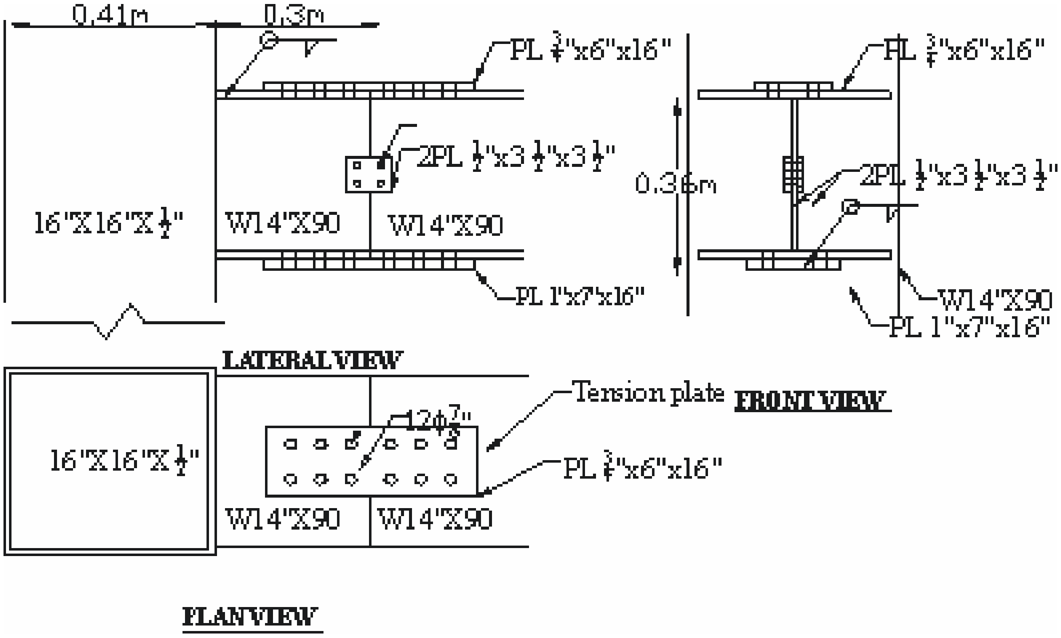

Figure 4. Views of critial joint, bolted option of connection.

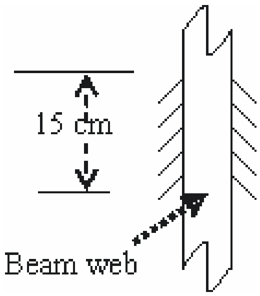

Figure 5. Alternative welded connection.

exceed the allowable moment and shear force at each connection and these thresholds were calculated for the bolt or welding resistance from the 0.60 of the ultimate stress for the bolt or welding. Specific repair techniques were not considered but, instead of that, the limit state function compared the maximum force (moment or shear force) to the corresponding resistance.

The costs and other economic data, for the building, are shown in Tables 1 and 2. It was considered that the worst scenario of human af-

Table 1
Costs data (USD)

Connection	1	2
Ci	20000	22000
Cr	8000	10000
LR	20000	20000
CIL	10000	10000
C1L	80000	80000

Table 2
Other economic data

γ	0.08
N_{in}	0
N_D	60
L	50 years

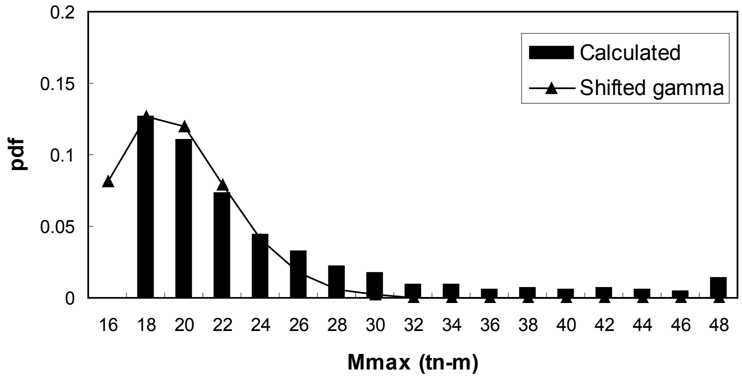

Figure 6. Annual maximum moment distribution for welded connection.

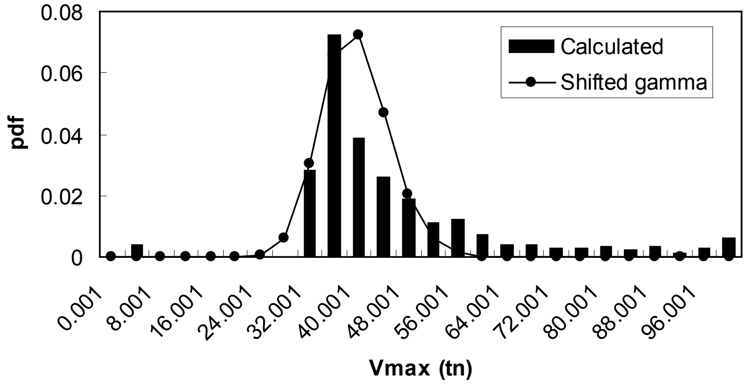

Figure 7. Annual maximum shear force distribution for welded connection.

fectation is when all the building occupantsdie and there are no injuries. The bending mode was found to govern the connection failure. The capacities for moment and shear force, for failure (f) and repair (rep) and for both connections are shown in Table 3. The repair and failure probabilities, for both connections, are shown in Table 4. With the above obtained failure probabilities, the expected life-cycle costs are calculated and the results are shown in Table 5.

Parametric studies

Two types of connections, bolted and welded, have been designed in such a way that the bending and shear resistances are similar, according to Table 3. The connections capacity is larger than the capacity of the beam and column and there might be some inelastic behavior in beam and column. This is included into the results as they consider the maximum acting force and the capacity of the connections. The ultimate capacity of the connections has been considered here although the full nonlinear moment-curvature behavior and ductility is not explicitly included at this stage of the study.

From inspection of the results, it is observed that the initial, repair and economic loss are the costs that dominate the selection of connection type. Therefore, the expected life-cycle cost is assessed for various values of these parameters. The results for several combinations of initial (construction) costs are shown in Figure 8.

If the cost of welding remains below 0.97 times the cost of the bolted connection, the welded connection is the recommended one. However, if the welding exceeds that limit, the connection should be bolted for the minimum expected life-cycle cost. Now, as far as the repair cost is concerned, the comparison of expected life-cycle costs, for a few combinations of repair costs for the bolted and welded connections proposed, is shown in Figure 9.

Table 3
Capacities for alternative connections

M_{f1} (tn-m)	V_{f1} (tn)
69.65	108.31
M_{rep1} (tn-m)	V_{rep1} (tn)
26.19	64.99
M_{f2} (tn-m)	V_{f2} (tn)
70.58	115.8
M_{rep2} (tn-m)	V_{rep2} (tn)
38.75	81.48

Table 4
Repair and failure probabilities
for alternative connections

$P_{r1\ M}$	P_{r2M}
0.007	2E-06
$P_{f1\ M}$	P_{f2M}
2E-07	1E-08

Whenever the welded connection costs less than 0.4 times the bolted one, it is more economical to do the welded one and, if this cost exceeds that limit, the bolted one is the one to be recommended. Finally, for losses due to business interruption (rent, for example) up to 200,000 USD, the bolted connection is preferred but, for losses higher than that, the welded connection is recommended (see Figure 10).

Discussion of results

For the two specific connections considered here, it is observed that recommended one is the bolted connection. The most important cost items were the initial (construction) cost, the repair cost and the losses due to service (business) interruption. The bending effect is the one that governs the connection design for the case treated here and

Table 5
Expected life-cycle costs for alternative connections

Alternative	$E[C_f]$	$E[C_{fat}]$	$E[L_r]$	C_i	$E[C_D]$	$E[C_T]$
1	630	1.87	1E02	2000	771.87	20771.87
2	0.17	0.09	3E-02	22000	0.29	22000.29

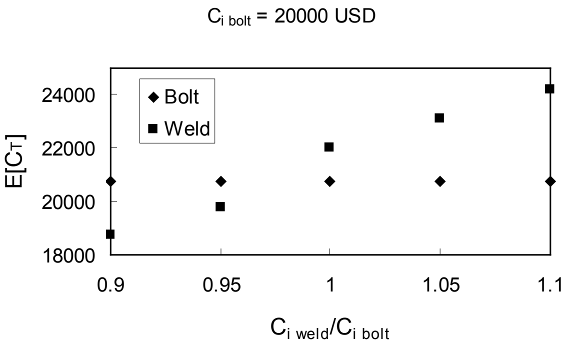

Figure 8. Expected lifecycle cost for several initial costs of welded connection.

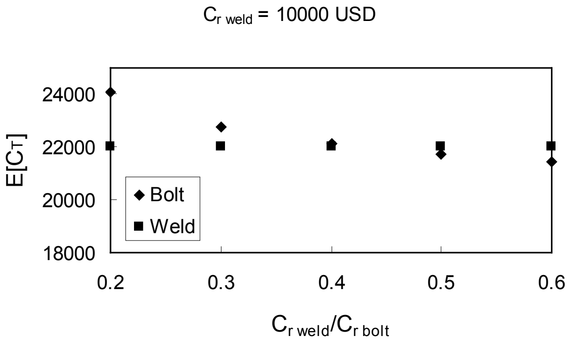

Figure 9. Expected lifecycle cost for several repair costs of bolted connection.

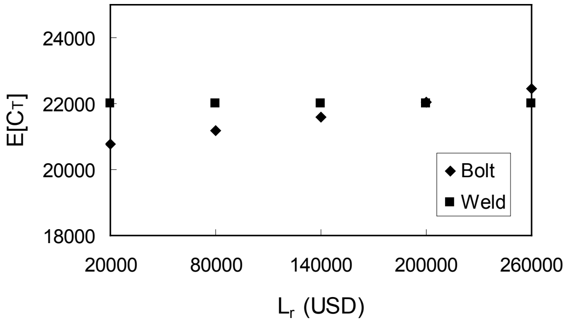

Figure 10. Expected lifecycle cost for several losses related to business interruption.

for the seismic conditions illustrated. This is not always the case and, for other cases of structural type, joints and seismic environment, the governing failure mode should be identified.

The cost differences regarding the initial and repair costs may be explained because, for the bolted connection, part of the work is made on a workshop and the rest "in situ" and no very specialized workmanship is required whereas, the welded one makes use of a more qualified certified (more expensive) workmanship. It is interesting to note that, for expensive service interruption losses, the gain on safety by the welded connection offsets the more expensive initial and repair cost. But, for cheaper service losses, the bolted connection is recommended. Two simple options were included here for illustration purposes and the findings apply only to this case. 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 a connection between 2 proposed types in a steel building under seismic loads. For the particular building considered here, the bolted connection is preferred, from the cost effectiveness point of view, over the welded one. The bolted connection is preferred when the initial cost of the welded one exceeds, at least 0.97 times, the cost of the bolted one, if the repair cost of the welded one exceeds, at least 0.4 times, the one of the bolted one and if the losses due to service interruption are less than 200,000 USD. Maximum moments and maximum shear forces are better characterized through shifted gamma distributions. Further research, with the analysis of many other structural types, number of stories, natural periods of buildings and a whole range of connection types and joints (including combinations of bolts and welding fillets), may help to update the Mexican code for design and retrofit specifications. In addition to that, the nonlinear behavior of bolted and welded connections should be included.

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