The 2015 World Congress on
Advances in Structural Engineering and Mechanics (ASEM15)
Incheon, Korea, August 25-29, 2015

Uniform annual failure rates spectra for post-tensioned structures

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ABSTRACT

A numerical algorithm to calculate uniform annual rate spectra for single-degree-of-freedom structural systems with post-tensioned connections, using the concept of energy, is proposed. In order to illustrate the steps of the algorithm, energy spectra corresponding to a specific site (located in soft soil of Mexico City) are calculated for different mean annual failure rates.

1. INTRODUCTION

The seismic design spectra corresponding to single degree of freedom (SDOF) are commonly used to obtain the maximum drift of structural buildings; however, in most seismic design codes around the world, these spectra have been obtained without explicitly considering the accumulated damage. One option to consider such damage is by using hysteric energy spectra. Dissipating energy can be very important especially in structures subjected to long duration seismic ground motions, like those occurred in soft soil of the valley of Mexico city during intense seismic events. Another limitation of most of the spectra recommended by seismic design codes is that reliability levels in structures are not explicitly considered, since most of the regulations are mainly based on studies of inelastic behavior SDOF systems, which does not guarantee the same exceedance rate between the response of SDOF and multi-degree-of-freedom (MDOF) systems. Several researchers (Wen, 1995; Ghosh and Collins, 2002; Rivera and Ruiz, 2007) have mentioned that, in general, the design spectra specified by design codes do not guarantee the same level of reliability in each of its limit design states.

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On the other hand, there are several approaches in the literature for the seismic design of conventional buildings; however, research on structural systems with post-tensioned connection and energy dissipation devices (PTFED) has been scarcely considered. López-Barraza (2014) analyzed a set of steel frames with post-tensioned connections; however, were not considered uniform failure rate spectra.

The advantage of using PTFED is the ability to achieve comparable stiffness and resistance to those of conventional connections, as well as to allow for seismic energy dissipation. This behavior can be achieved without the occurrance of inelastic deformations in beams and columns, and residual deformations. This occurs because the connections with post-tensioned and energy dissipation devices include high resistance steel strands (which remains elastic during the seismic response), while the seismic energy dissipation is limited to what is designed to develop large deformations in the inelastic range (steel angles).

Rivera and Ruiz (2007) obtained spectra with uniform annual failure rates for structures with energy dissipating elements with bilinear behavior; however, these spectra were obtained using ductility as the parameter of the systems. In the present study the response parameter is the hysteretic energy.
In the literature several approaches, where energy spectra are used to take into account uniform failure rates (Bojorquez and Ruiz, 2004; Bojorquez et al, 2008; Bojorquez and Rivera, 2008) have been proposed; however, were considered conventional systems. As previously mentioned, in this paper hysteretic energy spectra with uniform annual failure rate (ESUFR) of PTFED are calculated.

2. ESUFR FOR STRUCTURES WITH POST-TENSIONED CONNECTIONS

The structural model used here to represent the SDOF system and the post-tensioned connections together with the energy dissipating elements is constituted by a simple oscillator with two springs in parallel: one for the connection and one for the structure.

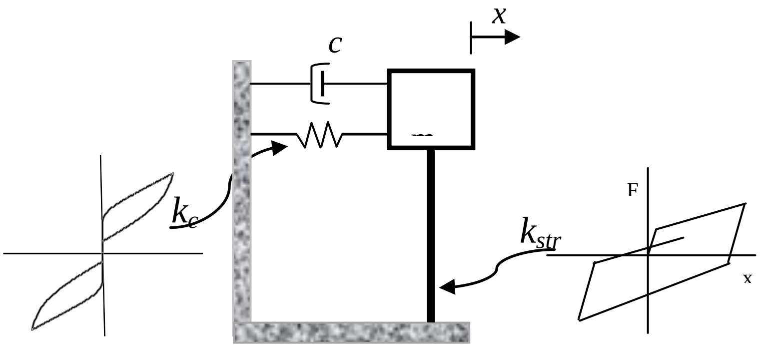


Fig. 1 Equivalent SDOF system with post-tensioned connections

The mathematical model of the system shown in Fig. 1 is given by the non-linear equation (Rivera, et al 2014):

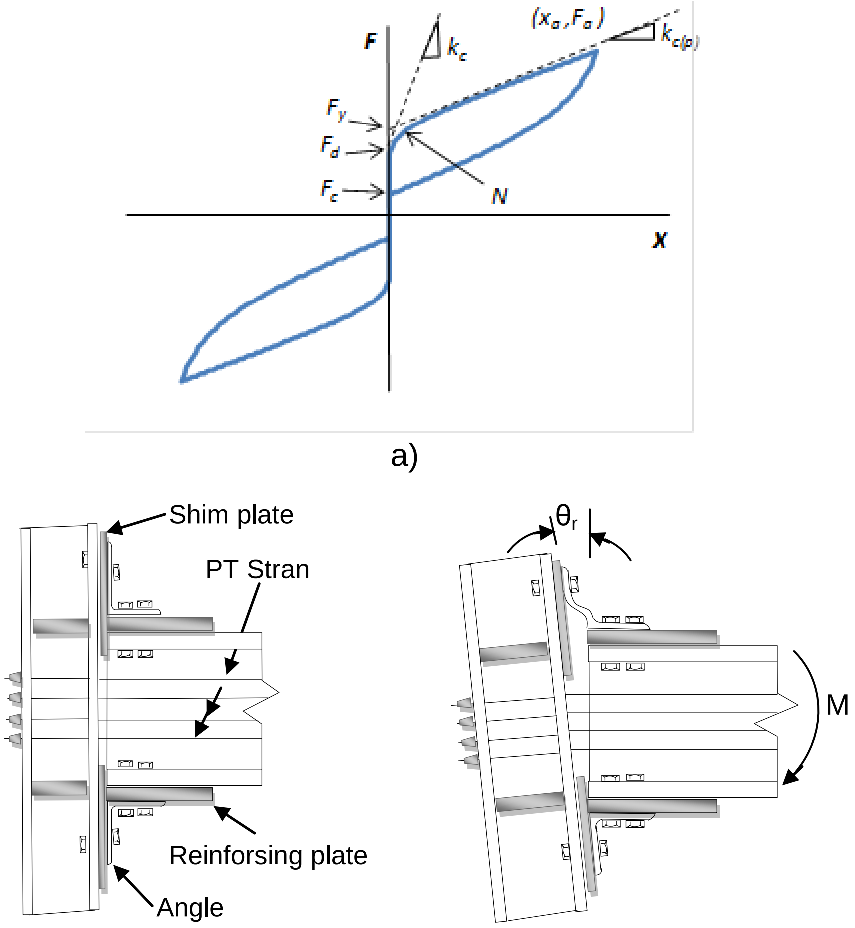
$$
\begin{gathered}
\ddot{x} = -\frac{c}{m}\dot{x} - \frac{k_{str}}{m}\alpha_2 x - (1-\alpha_2)\frac{k_{str}}{m}z - \frac{F}{m} - \ddot{x}_g \\
\dot{z} = \frac{\alpha_3\dot{x} - \upsilon\left(\alpha_4 z|\dot{x}||z|^{\alpha_6-1} + \alpha_5\dot{x}|z|^{\alpha_6}\right)}{\eta}
\end{gathered}
\qquad (1)
$$

where $\ddot{x}$, $\dot{x}$ and x are the acceleration, velocity and displacement, respectively; m is the mass, c is the damping, k_{str} and k_c are the stiffness of the main structural system and of the connections, respectively; α_2 is the ratio between the post yield structural stiffness and the initial stiffness; z is the hysteretic component; $\alpha_3, \alpha_4, \alpha_5$ and α_6 are parameters of the model proposed by Bouc (1967) and modified by Baber and Wen (1981). In addition, Eq. (1), F is obtained as follows:

$$
F = F_d + \frac{(k_c + k_{c(p)})x}{\left[1 + \left|\frac{(k_c - k_{c(p)})x}{F_0}\right|^N\right]^{\frac{1}{N}}} + k_{c(p)}x \qquad (2a)
$$

$$
F = F_a - \frac{(k_c + k_{c(p)})(x_a - x)}{\left[1 + \left|\frac{(k_c - k_{c(p)})(x_a - x)}{\beta F_0}\right|^N\right]^{\frac{1}{N}}} - k_{c(p)}(x_a - x) \qquad (2b)
$$

where $k_{c(p)}$ is the post-yielding stiffness of the connection, N defines the transition zone from elastic to inelastic behavior; β defines the width of the flag; F_d is the decompressing force (exactly when the connection opens); $F_0=F_y - F_d$ (where F_y is the yield force); x_a and F_a are the maximum displacement and maximum force reached in each load cycle, respectively. Eq. (2a) is used for either positive or negative load cycles; while Eq. (2b) is for unloading. The parameters previously mentioned are indicated in Fig. 2 which shows a hysteretic cycle of the semi-rigid post-tensioned connection; In this figure, F_c is the force when the connection closes. Eq. (2a) and (2b) are based on experimental tests obtained by López-Barraza et al. (2014). Fig. 2 illustrates the behavior of the connections.



a)

b)

Fig. 2 a) Hysteretic behavior of the PTFED; b) PTFED behavior

2.1 Numerical algorithm proposed to obtain ESUFR

The numerical algorithm proposed to obtain ESUFR corresponding to PTFED systems is as follows:

1. As a first step, the values of the following parameters are proposed: nominal structural vibration period (*T*) for the combined system (SDOF system plus post-tensioned connections), stiffness for the combined system (k_{tot}), the γ value that represents the ratio of stiffness of the structure and connections ($\gamma = k_{str}/k_c$), yield displacement of the combined system d_y, and the connections properties (F_d, F_0, N and β).

2. The mass of the SDOF system is calculated ($m = k_{tot}T^2 / 4\pi^2$). The stiffness of connections and structure are obtained ($k_c = \frac{k_{tot}}{1+\gamma}$ and $k_{str} = k_{tot} - k_c$).

3. Parameters of the Bouc-Wen model are proposed. In the present study the following values were used: $\alpha_3 = 1;\ \alpha_6 = 15;\quad \alpha_4 = \alpha_5 = \frac{1}{2}\left(\frac{k_{str}}{F_{y(str)}}\right)^{\alpha_6}$.

4. Each SDOF system with PTFED is subjected to a set of simulated accelerograms. In the present study the seismic ground motions were generated based on the record obtained in September 19, 1985 at the Ministry of Communications and Transport (SCT) station, located in soft soil in Mexico City, and scaled to a spectral acceleration (S_a) corresponding to a specific value of structural period *T*.

5. The maximum displacement is obtained "step by step"method in time domain. The energy demand of the combined system is calculated by solving Eq. (1).

6. Uniform annual failure rate for SDOF system with PTFED is calculated with Eq. (3) (Esteva, 1969, Esteva and Ruiz, 1974):

$$\nu_F = \int \left|\frac{\partial \nu}{\partial y}\right| P(Q \geq 1 | y)dy \tag{3}$$

where $\left|\frac{\partial \nu}{\partial y}\right|$ is the absolute value of the derivative of the site seismic hazard curve (which is assumed to be known), $P(Q \geq 1|y)$ is the conditional probability that the structural failure occurs, given a seismic intensity y.

7 The conditional probability $P(Q)$ is calculated for the parameters k_{tot}, γ, F_d, F_0, *N*, *β* and for different values of *T*, as the seismic response in terms of energy of a SDOF that exceeds a target value of hysteretic energy, between the number of simulated records. With the numerical evaluation of Eq. (3), demand hazard curves of the combined system, associated to different structural periods are obtained. The curves obtained for the parameters assumed in the present study are shown in Fig. 3. The vertical axis of the figure represents the mean annual exceedance rate, and the horizontal axis the dissipated energy.

8. Finally, the energy spectra with uniform annual failure rate (ESUFR) are drawn (E_{HN} vs T). The ESUFR associated with Fig. 3 are presented in Fig. 4.

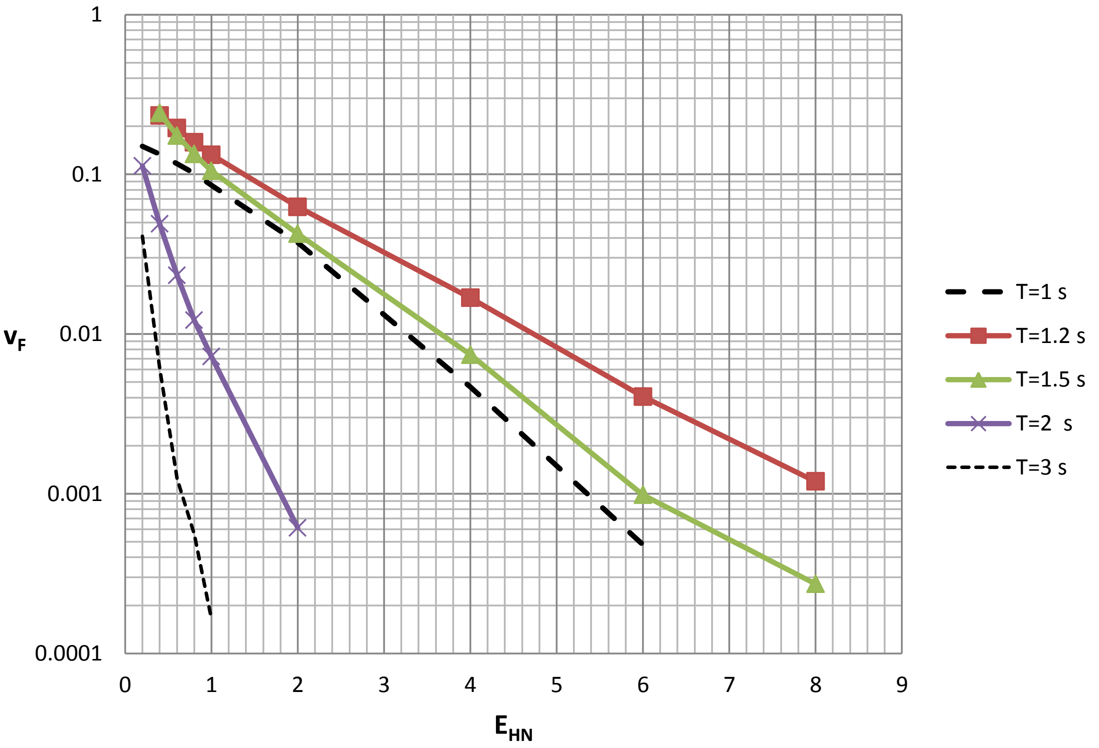


Fig. 3 Structural demand hazard curves with γ=0.189, d_y=0.07m and k_{tot}=2200000 N/m

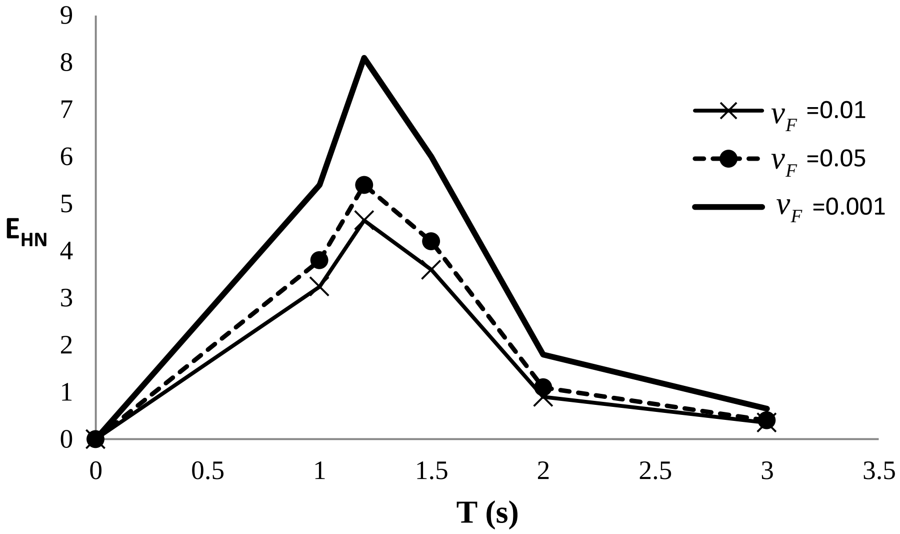


Fig. 4 ESUFR spectra of SDOF systems with post-tensioned connections

3. CONCLUSIONS

The numerical algorithm proposed here for obtaining energy hazard curves (E_{HN}-versus-ν_F) and, uniform failure rate energy spectra (ESURF) for SDOF systems with post-tensioned connections and dissipating element, has been systematized in a computer program.

The computer program may be applied by structural designers to obtain energy hazard curves and ESUFR that correspond to SDOF combined systems (located at a specific site) with given values of the parameters mentioned in section 2.1. The results could be used for design purposes.

ACKNOWLEDGEMENTS

This research project had the support of PROPAPI 2014/177 and of the DGAPA-UNAM (IN1022114). Part of the research was done while the first author was a visiting professor at the Universidad Nacional Autónoma de México.

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