INELASTIC RANDOM SEISMIC RESPONSE AND RELIABILITY OF DUCTILE FRAMES FILLED WITH BRITTLE ELEMENTS

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The lack of proper guidance on the seismic behavior of frames when filled with brittle elements like masonry infill walls in most design codes has motivated this study. Considering available experimental data, an idealized hysteretic model for the brittle element is proposed and incorporated into dynamic analysis program where inelastic response and reliability assessment are conducted under simulated ground motions. Approximate solutions for the average and standard deviation of accumulated plastic energy and ductility factor imposed on the frame are found in closed form expressions. In general, plastic energy and ductility demands-based infilled frame reliability is found to be higher relative to bare frame depending on the level and duration of input motion intensity and mechanical characteristics of the system.

Key words: inelastic random seismic response, reliability, infilled frame, brittle element, accumulated plastic energy, ductility factor

1. INTRODUCTION

Infill wall elements are often used for enclosing and partitioning spaces in office and residential frame building structures. The frame whose elements surround infill wall is called infilled frame. In case of masonry infill walls, they will be made from variety of local materials like hollow/solid bricks or concrete blocks with mortar bond. The infilled frame system is widely used in South Europe, Latin America, and most of the developing countries.

In most cases, infill walls are considered as nonstructural elements and their influence on the response of the surrounding frame is ignored in seismic design practice. However, recent experimental data and analytical studies have shown that introducing infill walls to bare frames enhance the lateral stiffness, strength and energy dissipation capacity of the bounding frames (Mehrabii, et al., 1996, Gabrilovic and Sendova, 1992, Broken and Bertero, 1981). Nevertheless, the research already made in this subject have failed to quantify the effect of infill walls on the overall seismic response of the surrounding frames in convenient forms for design purpose. It is the aim of this study to fill this gap by providing the average and standard deviation of the accumulated plastic energy and ductility demands in closed form expressions. Making use of these expressions, reliability analysis is performed taking into account different input parameters for the frame, infill wall, and input motion intensity level. The drawn reliability curves are also verified under the same conditions using probabilistic method.

2. INFILL WALL HYSTERETIC MODEL

Many available experimental data reported on the behavior of infilled frames show that infill walls reduce the plastic energy and ductility demands on the bounding frames. Experimental data also show a wide range of scatter as how much the infill wall is contributing to the overall stiffness, strength and energy dissipation capacity of infilled frame in different loading stages and conditions. This range of scatter could be attributed to many factors, of which are the different geometrical and mechanical characteristics of infill walls and their constitutive materials (for example, masonry units and mortar with/without grout, or other materials) and structural properties of the frame. Lateral stiffness of infilled frames may fall in the range between 5-20 times that of the surrounding bare frames and the corresponding shear strength ratio in the range between 1.4-2.5 times. However, it is indicated that as soon as infill wall reach its yielding strength, its stiffness and strength are rapidly dropped. This drop is externally caused by bond separation between the infill wall and the surrounding frame and internally by
excessive cracks and crushes reflecting the brittle behavior of infill wall under increased deformation demand. In general, idealized load-deformation relationship of infill wall, bare frame, and infilled frame could be roughly summarized in Fig. 1(a).

Based on previous investigation, a simplified multi-linear hysteretic model shown in Fig. 1(b) is proposed for modeling restoring force in infill wall element (Al-Sadeq and Matsushima, 1998). The model conservatively assumes sudden drop at ultimate strength and accounts for the brittle character of the element by considering negative post-yielding stiffness. The stiffness degradation is assumed proportional to strength reduction leading to a gradual failure of the infill wall element after which the infilled frame system behaves like bare frame. The controlling parameters are, initial stiffness \( (K_{w0}) \), yielding strength \( (Q_{y0}) \) and post-yielding negative slope of the envelope curve \( (\beta K_{w0}) \) where \( \beta \) is the ratio between the infill wall post-yielding stiffness to its initial stiffness. A bilinear elasto-plastic model with zero plastic stiffness shown in Fig. 1(c) is used for modeling restoring shear force in frame element which has initial stiffness \( (K_{f0}) \) and yielding strength \( (Q_{f0}) \) as controlling parameters which are assumed not to be affected by infill wall existence. Infilled frame initial stiffness \( (K_{w0}) \) and yielding strength \( (Q_{y0}) \) are taken as multiples \( R_q \) and \( R_y \) of the bare frame initial stiffness \( (K_{f0}) \) and yielding strength \( (Q_{f0}) \), respectively, i.e., \( R_q = K_{w0} / K_{f0} \) and \( R_y = Q_{y0} / Q_{f0} \), where it is assumed that \( K_{w0} = K_{f0} + K_{w0} \) \( R_y = Q_y + Q_{y0} \).

The proposed infill wall model is incorporated into a more general nonlinear dynamic analysis program DRAIN2D+ (Tsai and Li, 1994) for which, the infill wall element is decomposed into series of parallel sub-elements, each of which is assumed to have shear type load-deformation relationship. The stiffness and strength of the infill wall element are equally divided among the sub-elements and given gradually increased ductility in comply with the slope of the post-yielding envelope curve of the infill wall hysteretic model. A single sub-element will be failed once the given ductility is reached and the force which was holding will be transferred to the frame.

\[ Q(t) = Q_{yw}(t) = \begin{cases} 0 & \text{if } \delta(t) < \delta_y \text{ or } \delta(t) > \delta_y \\ \beta K_{w0} \delta(t) & \text{if } \delta_y \leq \delta(t) \leq \delta_y \\ \frac{Q_{yw}}{2} & \end{cases} \]

Figs. 1 (a): General Load-Deformation Relationship, (b): Hysteretic Model for Brittle Element, (c): Bilinear Ductile Frame Model

3. INPUT MOTION & SYSTEM INPUT DATA

A flat power spectral density function is assumed for generating one hundred statistically independent white noise acceleration time histories used as input motions. Response analysis is performed for four levels of \( \xi \) which denotes the ratio of the input motion intensity to the bare frame strength. \( \xi \) is defined as \( \xi = \omega_0 S_0 / \alpha^2 \) in which, \( \omega_0 \) denotes the bare frame initial circular frequency given by \( \omega_0 = 2\pi / T_0 \) where \( T_0 \) is its initial natural period of vibration, and \( S_0 \) is the constant spectral density of the excitation. The typical chosen gradually increased values for \( \xi \) are 0.0125, 0.025, 0.0375 and 0.05. Infilled frame stiffness ratio \( R_q \) is taken as 1, 6, 8, 10, 12 and 14 and for the corresponding yielding shear strength ratio \( R_y \), the values 1.0, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9 and 2.0 are considered. The value of unity in \( R_q \) or \( R_y \) corresponds to bare frame condition which is viewed here as a special case of infilled frame. The post-yielding stiffness ratio of the infill wall model is taken as \( \beta = 0.2, -0.1 \), and -0.05. In this study, the considered values for \( R_q \), \( R_y \) and \( \beta \) parameters are concluded from investigating the available experimental data and considered to cover wide range of infilled frame structural characteristics. Any combination of \( R_q \), \( R_y \), \( \beta \) and \( \xi \) values, corresponds to one case of analysis. The adopted ranges of \( R_q \), \( R_y \), \( \beta \), and \( \xi \) form totally 424 analytical cases.

4. NONLINEAR RESPONSE ANALYSIS

Infilled frame is idealized by undamped mass-spring system having single degree of freedom. The system has restoring force equal to the sum of two hysteretic loops which are the infill wall hysterosis proposed in this study and shown in Fig. 1(b) and the frame hysterosis shown in Fig. 1(c). The equation of motion is given by:

\[ m \ddot{x}(t) + \frac{Q_{yw}(t)}{m} = -\ddot{x}_y(t) \]  

(1)

where \( x(t) \) is the system relative displacement with respect to its base and dots denote the second derivative with respect to time. \( Q_{yw}(t) \) represents the restoring force of the infilled frame which has oscillating mass \( m \) and \( \ddot{x}_y(t) \) is the stationary white noise taken as horizontal ground acceleration for exciting a system initially resting on the ground. The attention is focused on two important response
quantities, i.e., average plastic energy dissipated by frame element $E_p$ which has its normalized form $\bar{\lambda}$ given by $\bar{\lambda} = E_p / Q_p \delta_p$, and average ductility factor $\bar{\mu}$ defined here as the average maximum absolute displacement divided by frame yielding displacement. Standard deviations for $\lambda$ denoted by $\sigma_\lambda$ and for $\mu$ denoted by $\sigma_\mu$ are computed as well.

4.1 Average Accumulated Plastic Energy
Due to space limit, only part of $\bar{\lambda} - \tau$ simulated curves are displayed in Fig. 2 in solid lines where $\tau$ represents the non-dimensional time defined as $\tau = t / T_0$ which lies between 0 - 40.

![Fig. 2 Expected and Predicted Curves of Plastic Energy ($\beta = -0.1$)](image)

Matsushima (1991) has found that $\bar{\lambda}$ in the stationary state is given by $\bar{\lambda} = 2\pi^2 \bar{\xi} (\tau - \tau_0)$ in case of bare frame condition, where $\tau_0$ is the expected non-dimensional time for the response to arrive at elastic limit. In an attempt to draw up a general formula capable of predicting $\bar{\lambda} - \tau$ curves in any state including transient one and when infilled frames are concerned, statistical computations are made on the simulation estimates. It is found as shown in Fig. 3 (general case) that the second term in the previous formula is a function of $\tau$ as far as the infill wall is in the functioning state, but becomes constant value once the complete failure of the infill wall has occurred after which infilled frame turn to behave like bare frame. It is found that the predicted value of $\bar{\lambda}$ could be given in the following formula:

$$\bar{\lambda} = a_1 \left( \tau - \tau_c \left( 1 - e^{-\tau / \tau_c} \right) \right)^{b_1}$$  \hspace{1cm} (2)

where $a_1$ and $b_1$ are taken as $a_1 = 2\pi^2 \bar{\xi}$ and $b_1 = 1$. In the limits of $\bar{\lambda}$ formula, $\lim (\bar{\lambda} \tau \to 0$ as $\tau \to 0$ and $\lim (\bar{\lambda} \tau \to \infty$) as $\tau \to \infty$. Also, the slope of $\bar{\lambda}$ is decreased to zero as $\tau$ approaches zero, i.e., $\lim (d\bar{\lambda} / d\tau) = 0$ as $\tau \to 0$. $\tau_c$ is selected such that formula (2) fits the simulation data by means of least squares technique. The parameter $\tau_c$ is found to be function of three variables $\bar{\xi}$, $\epsilon / \bar{\xi}$ and $\beta$. Parameter $\epsilon$ is defined as $\epsilon = A_e / A_f$, where $A_e$ and $A_f = Q_p \delta_p$ are the shaded areas as shown in Figs. 1(b) and (c), respectively. $\epsilon$ can also be written in terms of $R_q$, $R_p$ and $\beta$ as in expression (4). Best fit is obtained when the parameter $\epsilon / \bar{\xi}$ falls in the range $0 \leq \epsilon / \bar{\xi} \leq 32$ for which $\tau_c$ is concluded in formula (3):

$$\tau_c = r \bar{\xi}^2 - \frac{\mu}{\beta} \left( e^{\epsilon (\epsilon / \bar{\xi})} - 1 \right)$$  \hspace{1cm} (3)

$$\epsilon = \frac{\left( R_q - 1 \right)^2}{2(R_k - 1)} \left( 1 - \frac{1}{\beta} \right)$$  \hspace{1cm} (4)
Parameters $r$, $s$, $u$ and $v$ in $\tau_c$ formula are found by best fitting methods and the following values are obtained as results: $r = 0.242$, $s = -0.429$, $u = 0.0407$ and $v = 0.164$. As can be noted, the first term in the right hand side of formula (3) is a function of $\frac{\tau}{\xi}$ which is frame and input motion related parameter whereas the second term is a function of $\frac{\tau}{\xi}$ and $\beta$, giving the infill wall contribution to $\tau_c$ value where it is found that $\tau$ parameter is an important index of the infill wall energy capacity relative to frame elastic strain energy. In the limits of $\tau_c$, when $\xi \rightarrow \infty$ then $\tau_c \rightarrow 0$ and when $\tau \rightarrow 0$ then $\tau_c \rightarrow 0.242 e^{-0.429}$ the case which corresponds to bare frame condition. The dashed lines in Fig. 2 stand for $\lambda$ prediction based on formula (2). It is noticed that good agreement between the predicted and simulated estimates are found in most cases.

4.2 General Formula Set-Up

Sampling simulated curves for the rest of the response quantities, i.e., $\bar{\mu} - \tau$, $\sigma_\lambda - \tau$ and $\sigma_\mu - \tau$ are displayed in solid lines in Figs. 4(a), (b) and (c), respectively. Formulations of these quantities are performed by analyzing their corresponding simulation estimates. It is realized that the general form of $\lambda - \tau$ relation prescribed in Eq. (2) could be maintained and generalized to account for the other quantities as written in Eq. (5) where $\tau_c$ is kept unchanged as defined earlier in Eq. (3) leaving only the parameters $a_i$ and $b_i$ to be defined using best fitting techniques. It is found that $a_i$ and $b_i$ can be written in terms of $\xi$ and/or $e / \xi$ as the following:

$$
\begin{align*}
\bar{\lambda} &= \frac{a_1 (\tau - \tau_c (1 - e^{-\tau / \tau_c})^b)}{1 - e^{-\tau / \tau_c}} \\
\bar{\mu} &= \frac{a_2 (\tau - \tau_c (1 - e^{-\tau / \tau_c})^b)}{1 - e^{-\tau / \tau_c}} \\
\sigma_\lambda &= \frac{a_3 (\tau - \tau_c (1 - e^{-\tau / \tau_c})^b)}{1 - e^{-\tau / \tau_c}} \\
\sigma_\mu &= \frac{a_4 (\tau - \tau_c (1 - e^{-\tau / \tau_c})^b)}{1 - e^{-\tau / \tau_c}}
\end{align*}
$$

(5)

where $i = 2, 3$ and 4 corresponding to $\bar{\mu}$, $\sigma_\lambda$ and $\sigma_\mu$, respectively. The coefficients $c_1$, $d_i$, $g_i$, $h_i$ and $j_i$ for each quantity are found using best fitting methods as done before and their resulting values are given in Table 1. Accordingly, the corresponding predicted curves for $\bar{\mu} - \tau$, $\sigma_\lambda - \tau$ and $\sigma_\mu - \tau$ are plotted in dashed lines in Figs. 4(a), (b) and (c), respectively. It can be seen that acceptable agreement between the simulated and predicted estimates are found in most cases from practical viewpoint. However, to know how well the fitting is, fitting ratio $f_i$ defined here as the prediction estimate divided by simulation value is investigated. It is found that $f_i$ is mainly related to $\xi$ and $e / \xi$ parameters, where it tends to increase when $e / \xi$ goes higher and if $\xi$ is kept constant, $f_i$ will be higher for lower value of $\xi$. For most cases, it is found that $f_i$ falls within the range (0.901-1.10) for $\lambda$ and $\bar{\mu}$, and within the range (0.85-1.15) for $\sigma_\lambda$ and $\sigma_\mu$. The upper limits of $f_i$ are mostly accompanied by lower value of $\xi$ and/or higher value of $e / \xi$. Nevertheless, still caution may be taken for some exceptional cases in which $f_i$ may go beyond the above ranges. These cases especially arise when $\xi$ in the lowest level (0.0125) and simultaneously $e / \xi$ in the upper range, also, under this situation, simulation results with double curvatures are noticed for $\sigma_\lambda$. Generally, $f_i$ is less for the averages than for the standard deviations which is preferable tendency as the importance of averages is more than standard deviations. On the other hand, the denominator of $f_i$ ratio is not perfectly exact itself due to sample size limit, therefore for reference, confidence intervals for the averages and variances are computed with 90% confidence level. For $\lambda$, the coefficient of variation is found around the range (0.2-0.5) and if the upper range is used with sample size of 100, confidence interval will be $< \bar{\lambda} > \pm 0.90 = \bar{\lambda}$ (0.91; 1.09). Similarly, the coefficient of variation for $\bar{\mu}$ is found around the range (0.4-0.6) and using the upper value results in $< \bar{\mu} > \pm 0.90 = \bar{\mu}$ (0.90; 1.10). Besides, the variance's confidence interval is found to be $< \sigma^2 > \pm 0.90 = \bar{\sigma}$ (0.80; 1.28). For the averages, it can be noted that fitting ratios and confidence intervals are almost of the same order, and for variances, where relative errors are approximately twice as much as those for standard deviations, fitting ratio and confidence interval can also be viewed as having the same order. As we seek rough estimation of $\lambda$, $\bar{\mu}$, $\sigma_\lambda$ and $\sigma_\mu$ for preliminary design purpose, it is believed that those response quantities are still estimated within acceptable resolution.

The already developed formulas for $\lambda - \tau$, $\bar{\mu} - \tau$, $\sigma_\lambda - \tau$ and $\sigma_\mu - \tau$ response quantities, are also proved to have the same general form with their coefficients $a_i$ and $b_i$ having expressed in terms of two independent variables $\xi$ and/or $e / \xi$, whereas the coefficient $t_i$ is expressed as a function of $\xi$, $e / \xi$ and $\beta$. $\xi$ term takes the frame influence, $e / \xi$ and $\beta$ terms consider the influence of infill wall. However, it is noticed that when $e / \xi$ getting smaller, the importance of $\beta$ itself becomes less visible. The displayed curves for $\lambda$, $\bar{\mu}$, $\sigma_\lambda$ and $\sigma_\mu$ also show the relative importance of the infilled frame yielding strength ratio $R_f$ over its corresponding initial stiffness ratio $R_s$ which is indicated in $\xi$ formula as well. For specific infill, the importance of $\xi$ is prevailing in determining the degree of the influence of infill wall on the surrounding frame inelastic response.
Fig. 4 Simulated and Predicted Curves of $\bar{\mu}$, $\sigma_k$, and $\sigma_\mu$ ($\beta = -0.1$)
The plotted figures so far, corresponds to $\beta = -0.1$ as it is viewed most practical, but the above formulations are derived and hold applicable when the value of $\beta$ falls within the range $-0.2 \leq \beta \leq -0.05$. A sampling cases are considered and displayed in Fig. 5 where it is noted that applicability of the formulations in the two limits of $\beta$, i.e., $\beta = -0.2$, $\beta = -0.05$ which are physically viewed as two extreme values ranging from very brittle to less brittle infill wall elements, is also found to be satisfactory in most cases e.g., $f_i$ discussion.

![Fig. 5 Verification for other values of $\beta$](image)

**4.3 Relation between Response Quantities**

The relation between average ductility factor of frame element $\bar{\mu}$ and average normalized plastic energy dissipated by frame element $\bar{\lambda}$ is examined based on the simulation estimates and the derived formulas. Also, similar investigation is performed between their corresponding standard deviations, i.e., $\sigma_{\mu}$ and $\sigma_{\lambda}$. Figs. 6(a) and (b) display sampling simulated and predicted curves of $\bar{\mu} - \bar{\lambda}$ and $\sigma_{\mu} - \sigma_{\lambda}$, respectively. The predicted curves are plotted based on $\bar{\lambda}$, $\sigma_{\mu}$, $\bar{\mu}$ and $\sigma_{\mu}$ formulas evaluated earlier. The agreements between the expected and predicted estimates are satisfactory in most cases and for both $\bar{\mu} - \bar{\lambda}$ and $\sigma_{\mu} - \sigma_{\lambda}$ relations. In case of bare frame with bilinear hysteresis, Matsushima (1991) gave direct expressions for the above relations as $\bar{\mu} = \rho \bar{\lambda} + 1$; $\rho = 115.5 + 0.649$ and $\sigma_{\mu} = \psi \sigma_{\lambda}$; $\psi = 2.14=0.046$. The two relations are plotted by dotted lines in Figs. 6(a) and (b), respectively, where they correspond to the cases of ($R_q = 1.0; R_q = 1.0$: bare frame) from which it could be noticed that the general derived formulations in this study for bare/infilled frames are generally in consistent
manner with previous research. The nonlinear dynamic response of infilled frame system could be efficiently predicted by making use of the derived closed form expressions for \( \dot{\lambda} \), \( \sigma_L \), \( \mu \) and \( \sigma_m \). If \( \beta \) is kept constant, influence of infill wall on the response of the frame is taken up through a single factor \( e \) and entry for any expression is set through two separate variables, \( \xi \) which is a factor covering frame characteristic and input motion level, and \( e / \xi \) ratio which is an indicator of infill wall structural performance relative to \( \xi \). In general, the above figures show that infilled frames experience less damage relative to bare frames, in particular when dealing with low to moderate input motion intensity.

5. RELIABILITY ANALYSIS

Reliability function of the infilled frame system is defined here as the probability that the frame demands of accumulated dissipated plastic energy or ductility factor do not exceed some critical levels beyond which the system is assumed to fail. Reliability assessments are performed by making use of the previously derived formulas for the mean and standard deviation of plastic energy (\( \lambda, \sigma_L \)) and ductility factor (\( \mu, \sigma_m \)) in combination with appropriately selected probability density functions (p.d.f.s). Reliability functions for \( \lambda \) and \( \mu \), denoted by \( R_\lambda(\lambda_F) \) and \( R_\mu(\mu_F) \), respectively, can be defined in the following two integrals:

\[
R_\lambda(\lambda_F) = \int_0^{\lambda_F} f_\lambda(\lambda) \, d\lambda
\]

(8);

\[
R_\mu(\mu_F) = \int_0^{\mu_F} f_\mu(\mu) \, d\mu
\]

(9);

where \( \lambda_F \) is a prescribed extreme value of \( \lambda \) after which failure occurs which corresponds to \( \mu_F \) in case of \( \mu \). \( f_\lambda(\lambda) \) and \( f_\mu(\mu) \) are the probability density functions under which \( \lambda \) and \( \mu \) are assumed to be distributed. Figs. 7(a) and (b) show sampling cases of \( R_\lambda(\lambda_F) - \tau \) and \( R_\mu(\mu_F) - \tau \) curves which are conducted for three types of p.d.f.s, namely, lognormal, Gumbel and Gamma. It is concluded that \( R_\lambda(\lambda_F) \) and \( R_\mu(\mu_F) \) curves are irrelevant to distribution type in most cases. As different distribution types have given similar results, typical curves of \( R_\lambda(\lambda_F) - \tau \) and \( R_\mu(\mu_F) - \tau \) are computed and depicted in Figs. 8 and 9 (dashed lines) using Gumbel distribution for values of \( \xi = 0.025, 0.0375 \) and 0.05, \( R_\lambda \) = 1.0, 1.6, 1.8 and 2, and for \( R_\mu = 1, 6 \) and 8. The critical failure levels of \( \lambda_F \) and \( \mu_F \) are given the values of 10 and 5, respectively. The probability density function and cumulative distribution function for Gumbel distributed accumulated plastic energy \( \lambda \), are written in Eqs. (10) and (11), respectively as the following:

\[
f_\lambda(\lambda) = \frac{1}{\rho_\lambda} \exp \left\{ \frac{\lambda - \chi_\lambda}{\rho_\lambda} - \exp \left[ \frac{\lambda - \chi_\lambda}{\rho_\lambda} \right] \right\}
\]

(10);

\[
F_\lambda(\lambda) = \exp \left[ - \exp \left( \frac{\lambda - \chi_\lambda}{\rho_\lambda} \right) \right]
\]

(11);

where \( \chi_\lambda \) and \( \rho_\lambda \) are expressed as functions of the average and standard deviation of \( \lambda \) and can be given in Eqs. (12) and (13), respectively.

\[
\rho_\lambda = \sigma_\lambda \sqrt{6} / \pi
\]

(12);

\[
\chi_\lambda = \lambda - \gamma (\sigma_\lambda \sqrt{6} / \pi)
\]

(13);

where \( \gamma \) in Eq. (13) stands for Euler’s constant which is equal to 0.5572. When ductility-based reliability is to be considered, \( \lambda \) as an index or main symbol in Eqs. (10), (11), (12), and (13) shall be replaced by \( \mu \). The simulated curves are displayed in the corresponding Figs. 8 and 9 (lines with symbols) where it is noticed that satisfactory agreement is reached in most cases from practical viewpoint. The reliability curves show how infill wall elements of different characteristics affect reliability of the frame element and the role that each controlling parameter takes in influencing the degree of effectiveness. Also, the curves are helpful tools for preliminary design purpose where system and earthquake data are usually available at this stage, then the probability of safety which is expressed in term(s) of reliability function(s) \( R_\lambda \) and/or \( R_\mu \) can be known. If the target safety level is found not appropriate, then system data have to be manipulated in order to get the prescribed target level of safety by means of trial and error methods.

It is found that the reliability of infilled frames also depends on three parameters represented by \( \xi \), \( e / \xi \) and \( \beta \). \( \xi \) is related to the frame yielding strength whereas \( e / \xi \) and \( \beta \) are related to infill wall potential energy capacity. Higher the value of \( \xi \) lower the reliability and more plastic energy and ductility are required and vice versa. But higher \( e / \xi \) higher reliability is available and less plastic energy and ductility is required from the frame element which is proved to indicate the importance that infill wall effect on the overall seismic response and reliability of frame systems must not be ignored. The bare/infilled frame reliability is treated through covering the uncertainty in the seismic loads by using simulated input motions and by allowing the geometric and mechanical characteristics of the system to be variable parameters in a way that enables the design engineer to practically estimate and judge the effect of the used brittle elements on the behavior of the designed frames by means of response quantities and/or reliability functions. However, there is still difficulty and unknown uncertainty in determining the infill wall parameters \( \beta \), \( R_k \) and \( R_q \) definitely, therefore, it is recommended that these parameters be considered as random variables in future study.
CONCLUSIONS

The nonlinear random seismic response and reliability assessment of infilled frame is presented. It is modeled by undamped single-degree-of-freedom system and subjected to simulated ground acceleration. The frame has elasto-plastic restoring force while infill wall has degraded stiffness and strength model. Accordingly, the following main points could be outlined:

1. Approximate solutions for the expectation and standard deviation of accumulated plastic energy and ductility factor demanded on the frame element, are derived as closed form expressions. The solutions are compared with the simulation estimates where acceptable agreement is found in most cases.

2. The influence of infill wall on the inelastic response and reliability of the frame is mainly related to infill wall potential energy capacity relative to the normalized input motion intensity.

3. The efficiency of infill wall in reducing plastic energy and ductility demands on the surrounded frame and enhancing its reliability is recognized to a level that depends on level and duration of input motion, infill wall potential energy capacity, and the frame structural characteristics.

REFERENCES


和文要約

1．序論

建築骨組構造では、空間を仕切るために壁要素（Infll Wall Element）が多く使われる。骨組要素が壁要素を含む場合、その骨組を壁付骨組と呼ぶことになる。多くの発展途上国ではこのような壁付骨組構造が広く用いられている。壁要素にはいろいろな材料が用いられる。例えば煉瓦やコンクリートブロックなどである。実際の設計では多くの場合壁と骨組はモルタルの付着だけで結合される。壁付骨組の地震時の非線形挙動については不明な点が多く、明確な設計指針もない。通常壁要素は非構造部材として無視される。そこで本論では壁付骨組の耐震性能を近似的に把握するために、非線形地震応答における骨組の累積塑性エネルギー及び塑性率の期待値と標準偏差を基本的な数式を導きを表すことを目標とする。またそれを用いて壁付骨組の耐震信頼性を評価する。

2．要素の履歴モデル

壁要素の履歴モデルを図1 (b)のように設定する。壁要素の履歴の特性は降伏後の復元力で表されている。剛性の低下は程度の低下に比例するとする。支配方程式は初期剛性（K_0）、降伏強度（Q_0）、及び降伏後の剛性（βQ_0）である。骨組要素の復元力は、図1（c）に示すバイリンニア形とし、塑性剛性はゼロとする。支配方程式は初期剛性（K_0）、降伏強度（Q_0）である。二つの新しいパラメータR_y (K_0/K_0) と R_s (Q_0/Q_0) を定義する。ここで、K_0=K_0/K_0及びQ_0=Q_0/Q_0である。壁付骨組の復元力は壁要素と骨組要素の復元力を足したものとする。要素損傷に応じて荷重が要素から骨組要素に移り、要素損傷の完全破壊後は壁付骨組の挙動は骨組だけの挙動と同じになる。

3．非線形応答解析

一定のパワースペクトル密度関数をもつ平均値ゼロの定常ホワイトノイズを入力加速度として、それを静止している非構造1自由度系の基部に作用させる。骨組要素の強度に対する入力の強度の比に相当する無次元変数ξを定義し、その値の範囲を0.0125～0.05とする。過去の関連する実験データを参照して、R_y = 1.3, 8, 14, R_y = 10, 20, 30, 40, 50, 60, 70 0.05, 0.10, 0.20 と設定する。R_y = 10, R_y = 10 は骨組要素のみの場合に相当する。骨組要素の無次元累積塑性エネルギーλの期待値と標準偏差（μ, σ_μ）及び塑性率μの期待値と標準偏差（λ, σ_λ）に注目する。それらの固有周期に無次元化された時間 t に依存する。λ と τ の関係は一般的に図3のようになり、（2）式のように書き表すことができる。シミュレーションの結果を表して、式中のtを（3）式の形に変換する。右辺の第1項は骨組要素だけの場合の τ_0 に相当している。第2項は要素損傷の影響を表す項で、ε/ξと τ の関数となっている。ここで、

εは図1（c）の形のついた四角形の面積に対する（b）の三角形の面積の比である。式中の定数は数値解に最も合うように決めると、図2のようにλの表処理は数値解とよく一致する。


4．信頼性解析

無次元累積塑性エネルギーまたは塑性率がそれぞれある規定された値λ_yを超えない確率を信頼性関数 R_y (λ_y) を設定する。信頼性関数は（8）（9）式のように対応する確率密度関数を求積することによって求められる。確率密度関数として対数正規分布、ガンベル分布及びガンブ分布の三つを仮定し、それぞれに得られた表現式を用いて信頼性を評価してみる。その結果により表4のように信頼性は確率密度関数の分布形により影響されることがわかる。そこでλ_yとμの信頼性関数を近似式で表される期待値と標準偏差を用いたガンベル分布であると仮定し、シュミレーションによって求められた信頼性関数と比較する。その結果の例を図8.9に示す。近似解と数値解はよく一致していることが分かる。骨組要素の信頼性は、ξ が大きいほど小さく、ε/ξが大きいほど大きい。

5．結論

塑性的要素（壁要素）を含む骨組の非線形地震応答の特性と信頼性について考察した。壁要素は降伏後に保とされる塑性特性をもと、骨組要素は完全弾塑性形塑性特性をもととした。壁付骨組構造を非構造1自由度系にモデル化し、定常ホワイトノイズを入力加速度とした非線形地震応答解析を行った。得られた結論は次のようにまとめられる。

1．骨組要素の無次元累積塑性エネルギー及び塑性率の期待値と標準偏差の近似解を求める形式の簡単な関数で表現し、それらを用いて信頼性解析を行った。シュミレーションの結果と近似解は実用的で許容できる範囲でよく一致した。

2．壁要素が骨組要素の応答を与える影響は、ε/ξと τの関数で与えられる。ここでεは骨組要素の塑性則決定エネルギーに対する壁要素の歪エネルギー値に相当するような量であり、εは無次元入力強度、ξは要素の塑性則特性を表す。近くにε/ξが壁要素の効果を表す重要な指標である。

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