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EVALUATION OF A DUAL-LEVEL DESIGN APPROACH FOR THE EARTHQUAKE RESISTANT DESIGN OF BUILDINGS

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ABSTRACT

A Dual-level seismic design procedure in which a building structure is designed for both an ultimate and a serviceability level force, is proposed and used to design a seven story reinforced concrete moment frame. The performance of the structure is monitored by a nonlinear pushover analysis and the design is adjusted accordingly. For comparison, a seven story reinforced concrete moment frame is also designed according to the 1991 NEHRP provisions. The two designs are modeled using DRAIN-2DX and subjected to 84 strong ground motion records from the 1994 Northridge Earthquake. Response quantities for the two designs, such as damage indices and global and local drifts, are compared. Using this data, the reliabilities of the two designs at different response levels, given an event similar to the Northridge Earthquake, are evaluated. It is concluded that the dual-level design procedure results in better drift and damage control for severe ground motions that force the building into the inelastic range. Thus, excessive structural and non-structural damage may be avoided with little or no interruption to the building occupation after the earthquake.

KEYWORDS

Dual-level design; seismic design; 1994 Northridge earthquake; Sylmar record, 1991 NEHRP provisions; PRESSS Guidelines; reliability; damage index; global drifts; local drifts.

INTRODUCTION

Although the earthquake resistant design philosophy of most building codes states that buildings should resist small earthquakes with no damage, moderate earthquakes with limited non-structural damage, and large earthquakes without collapse, the codes only require buildings to be designed for one ultimate force level. Thus, in effect, the buildings are only designed for the third criteria of the design philosophy. The extensive damage caused by the 1994 Northridge earthquake, and the unprecedented economic losses, have caused designers and owners alike to consider how the above design philosophy can be more fully realized in order to protect economic investments. This research proposes that a Dual-level design procedure may result in buildings that come closer to attaining the original design philosophy. Such a Dual-level design would require the building to remain elastic under a serviceability level force (corresponding to a design earthquake with a return period of, say, 10 years) and allow limited inelastic deformations under an ultimate level force (corresponding to the accepted 475 year return period).

Two seven-story reinforced concrete special moment resisting frames (SMRF) located in Los Angeles, California, are designed. One is designed according to the proposed Dual-level design procedure, while the other is designed by the 1991 NEHRP Provisions for New Buildings (BSSC, 1991). The two designs are subjected to 84 strong ground motion records from the January 17, 1994 Northridge earthquake. Response quantities from the two designs, such as, global roof drift, local interstory drift, and damage indices, are compared. The reliabilities, or probabilities of exceeding given thresholds for each response quantity, are evaluated for each frame. A method is developed to consider the distribution of epicentral distances in the reliability calculations.

DESIGN OF DUAL-LEVEL AND NEHRP FRAMES

The Dual-level design procedure generally follows the design philosophy in the "Ultimate Strength Design Guidelines for Reinforced Concrete Buildings" (PRESSS Guidelines, 1992), which is under review for adoption in Japan. Two limit states are considered in the Dual-level design: serviceability and ultimate. For each limit state an equivalent lateral force is applied and certain performance objectives are satisfied. For example, no flexural hinges should form under the serviceability level force, while the formation of flexural hinges should be limited to the beams and column bases to ensure a strong-column-weak-beam collapse mechanism under the ultimate level force. Furthermore, a static nonlinear pushover is required to determine if the maximum interstory drift remains under 0.5% for the serviceability level force and 2% for the ultimate level force (see figure 1). The equivalent lateral serviceability level force is derived from an **elastic** design response spectrum corresponding to a 10 year return period. The equivalent lateral ultimate level force is derived from a **reduced elastic** design response spectrum (i.e. a reduction factor = 1/0.15) corresponding to a 475 year return period. Further details of the PRESSS Guidelines and proposed Dual-level design may be found in Elwood and Wen, 1995.

Only the perimeter frames of the NEHRP design are used to resist the seismic loads. While many may argue with the effectiveness of perimeter frames for resisting seismic loads, this form of design remains common practice in California. The dual-level design, however, employs all frames to resist the seismic loading. The redundancy of the multiple frames should result in a more reliable structural system.

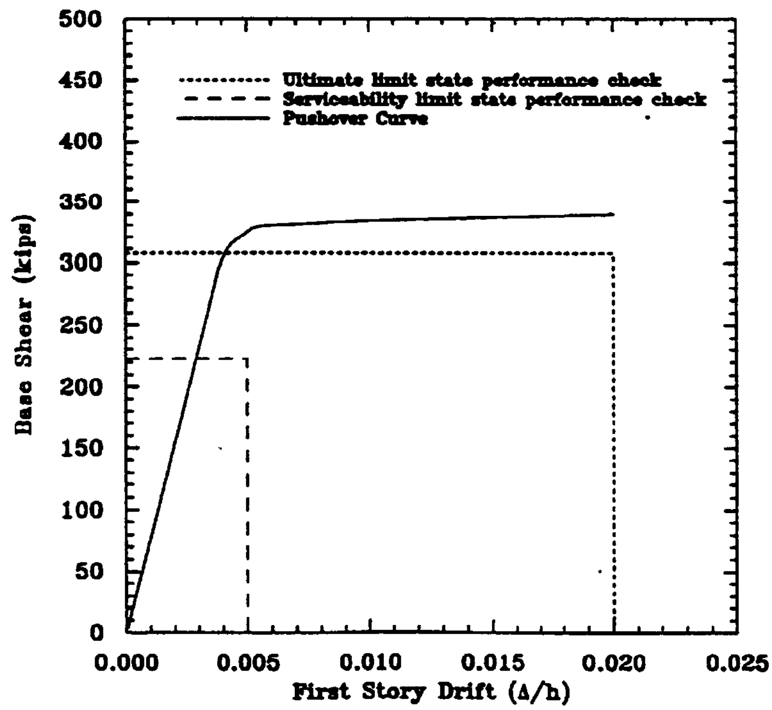

Figure 1: Performance Check for Dual-Level Frame

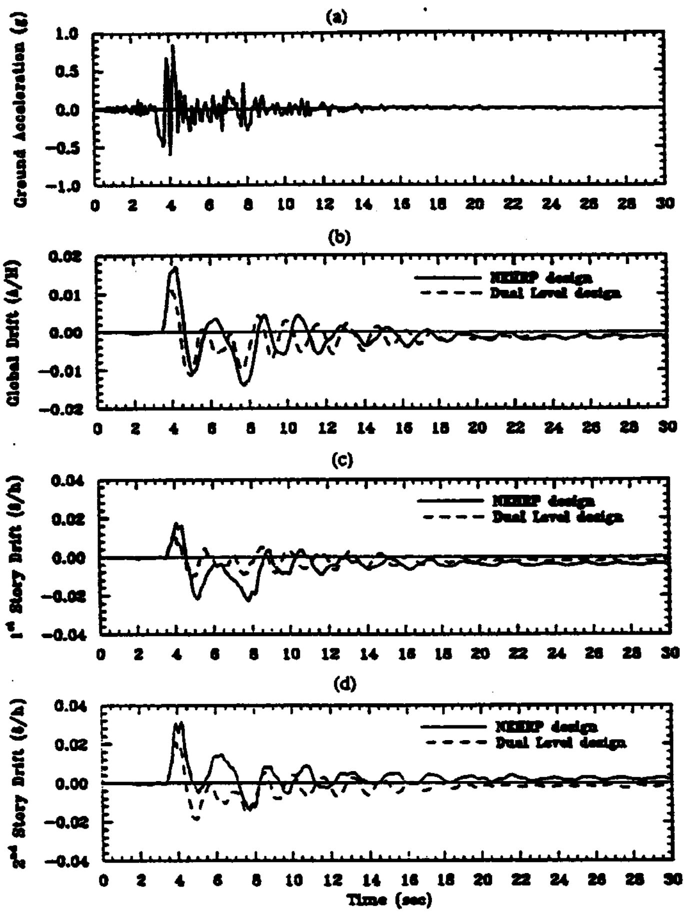

Figure 2: Ground Motion and Structural Responses for Sylmar Record
(a) ground acceleration, (b) global drift,
(c) first story drift, (d) second story drift

COMPARISON OF RESPONSES OF DUAL-LEVEL AND NEHRP DESIGNS

This section will discuss and compare the responses of the Dual-level and NEHRP frames modeled on DRAIN-2DX (Prakash, Powell, and Campbell, 1993) and subjected to the Sylmar strong ground motion record from the 1994 Northridge earthquake. Details of the DRAIN-2DX modeling can be found in Elwood and Wen, 1995. Three response quantities are compared: global roof displacement, local interstory drift, and damage indices. Damage indices are calculated according to a linear combination of damage due to excessive deformation and damage from repeated cyclic loading (Park, Ang and Wen, 1984).

The January 17, 1994 Northridge earthquake ($M_W = 6.7$) resulted in several near-field records, including one at the Sylmar County Hospital, 16 km from the epicenter. This record is characterized by two very large acceleration pulses (PGA = 0.91g). The significant strong ground motion lasts for only approximately 6 seconds, however, the blast of the initial shock is enough to cause significant damage. The Sylmar acceleration time history is shown in figure 2a.

The global drifts (i.e. the roof displacement as a fraction of the total height of the building) for both the NEHRP and Dual-level designs subjected to the Sylmar record are shown in figure 2b. The maximum global drift of the NEHRP design is 1.4 times that of the Dual-level design, and both occur within the first displacement excursion, indicating the importance of the blast of the initial acceleration pulse. The lower stiffness of the NEHRP design (T_{fund} = 2.12 seconds versus T_{fund} = 1.47 seconds for the Dual-level design) is evident in the longer period of vibration. The longer period of vibration may also be partially explained by the larger amount of inelastic deformation experienced by the NEHRP design. It is interesting to note that the final permanent global drift is essentially the same for both designs, and remains very small considering the large maximum displacement.

The local interstory drifts for the first and second stories of the two designs are shown in figures 2c and 2d. The maximum interstory drifts for the NEHRP design exceed that of the Dual-level design for both stories. It is interesting to note that while the global drifts of both designs remained below 2% (recommended by Sozen (1981) as a maximum limit for drift), the interstory drifts for the second story exceeded 3% and 2% for the NEHRP and Dual-level designs, respectively. This would appear to indicate a concentration of drifts in the lower stories. The interstory drifts for the second stories of both designs are generally larger than those for the first story, indicating the possibility of a soft story collapse.

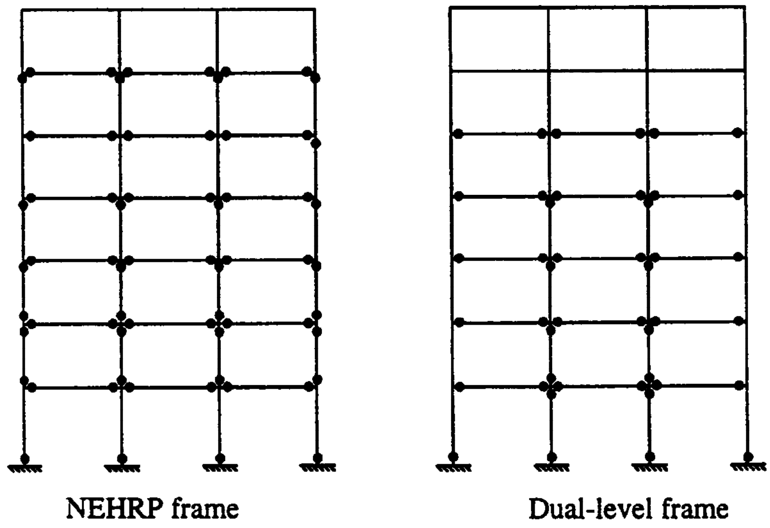

Figure 3: Flexural Hinges Resulting from Sylmar Record

Further understanding of the seismic performance may be gained by observing the distribution of flexural hinges throughout the two designs (see figure 3). Flexural hinges are formed when the moment at the end of a member exceeds the specified yield moment, and thus, hinges are still able to resist a moment of M_y (or higher if the strain hardening is included). It should be noted that no distinction has been made in figure 3 between hinges that have just barely yielded (i.e. small plastic hinge rotations) and hinges that have undergone extensive plastic hinge rotations.

For several stories (2, 3, 4, and 6) the NEHRP frame hinges have formed across all four columns, indicating the formation of a strong-beam-weak-column collapse mechanism. It does not necessarily lead to collapse since during an earthquake the inertial forces may be reversed by a reversal of the shaking motion. Nevertheless, the formation of a possible collapse mechanism threatens life safety, and thus, threatens the primary goal of the NEHRP provisions - to protect life safety during severe earthquake ground motion.

Although hinges have formed in many of the center columns of the Dual-level frame (see figure 3), no single story has hinges across all four columns (except at the base). Thus, a soft story collapse is not imminent. Formation of the hinges in the beams, prior to the columns, allows for increased hysteretic energy dissipation and evenly distributes the interstory drifts over the height of the frame. The improved performance of the columns in the Dual-level design may again be attributed to the performance check on the SCWB design.

The overall frame damage index for the NEHRP design is 0.98. This would suggest that the frame has experienced very nearly total collapse, thus not satisfying the life safety requirement of the NEHRP provisions. It should be noted that the DRAIN-2DX model assumes unlimited ductility in each member, and thus, is not able to detect member failure due to exceedance of the ultimate rotation capacity. The damage index attempts to detect this form of failure, and then determines the effect in the entire frame by weighting the individual member damage indices by the dissipated hysteretic energy. This explains why the time history of the global drift (figure 2b) does not suggest the collapse of the frame (i.e. no large permanent displacements), while the overall frame damage index suggests that collapse is imminent. The overall frame damage index for the Dual-level design is 0.78. According to the original Park, Ang, and Wen damage index model, this would suggest that the frame has suffered significant structural damage, but has not collapsed, and thus, has not threatened life safety. Since the Sylmar record was chosen to represent severe earthquake ground motions, the above performance may be considered acceptable. The damage indices are best used for a comparison of the seismic performance of the NEHRP and Dual-level designs. In this light, the Dual-level design performed much better than the NEHRP design for the Sylmar record.

The response quantities of the two designs are also compared for moderate and small ground motion records (Elwood and Wen, 1995). The results indicate that under small and moderate ground motions the Dual-level design remains nearly elastic, while the NEHRP design experiences significant yielding under moderate ground motions.

IMPLICATIONS OF THE 1994 NORTHRIDGE EARTHQUAKE TO DUAL-LEVEL DESIGN

Given the extensive number of strong ground motion records recorded during the 1994 Northridge earthquake, it is possible to evaluate the reliability of the NEHRP and Dual-level designs given an earthquake event similar to the 1994 Northridge earthquake. Since the location of future blind thrust fault events cannot be predicted, one can assume a reference area with a spatially uniform distribution of the epicenters. Or conversely, for a given event, the coordinates of the site can be assumed to be random and uniformly distributed within a circle reference area shown in figure 4. If x_1 and x_2 are the coordinates of a station and are uniformly distributed within a circle of radius R_{max}, then a station is more likely to be located in region B than in region A, even though $r_1 = r_3 - r_2$. Therefore, a more accurate representation of the distributions of response quantities should be obtained by considering the distribution of epicentral distances within the sample area, a circle of radius R_{max}.

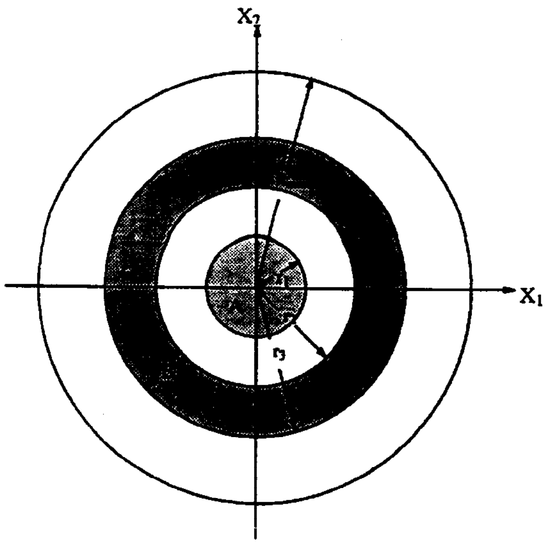

Figure 4: Reference Area of Radius R_{max}

Based on the total probability theorem and given the occurrence of the earthquake and a site within the reference area, the probability that a response X will exceed a given threshold x_o is given by:

$$P(X > x_o) = \int_0^{R_{max}} P(X > x_o | R = r) f_R(r) dr \tag{1}$$

where $f_R(r)$ is the probability density function of the epicentral distance. This conditional probability can be regarded as a measure of the performance of a building during future events similar to the Northridge earthquake, taking into consideration the random spatial distribution of the epicenter. If the coordinates x_1 and x_2 are uniformly distributed within a circle of radius R_{max}, then $f_R(r)$ may be expressed as:

$$f_R(r) = \frac{2r}{R_{max}^2} \tag{2}$$

The integral of equation 1 is evaluated numerically as follows:

$$P(X > x_o) = \sum_{i=1}^{84} P(X > x_o | R = r_{sta_i}) A_i$$

i.e. $$P(X > x_o) = \sum_{i=1}^{84} \frac{\#\text{of times } X > x_o \text{ at a distance } r_{sta_i}}{\#\text{of records at a distance } r_{sta_i}} \frac{2r_i}{R_{max}^2} \Delta r_i \tag{3}$$

Since the furthest station, has an epicentral distance of 98 km, R_{max} = 100 km was used to find the distributions presented later in this section

The above formulation does not consider the effect of the direction of the path from the Northridge epicenter to the station, *q*. This may be an important consideration since stations along the path of the fault rupture should produce severe records due to directivity effects. There are very few stations to the south-west and north-west of the epicenter due to the ocean and mountains, and thus, the uniform distribution of the samples is only approximately correct.

The probabilities of exceedance for the overall frame damage indices are shown in figure 5. The points designated by squares and triangles were calculated using equation 3. The fitted lines shown in figure 6 were calculated using a tail biased generalized extreme value distribution developed by Maes and Breitung (1993), which allows one to select a proper form of distribution with a greater weight at the tail, the region of interest in reliability analysis.

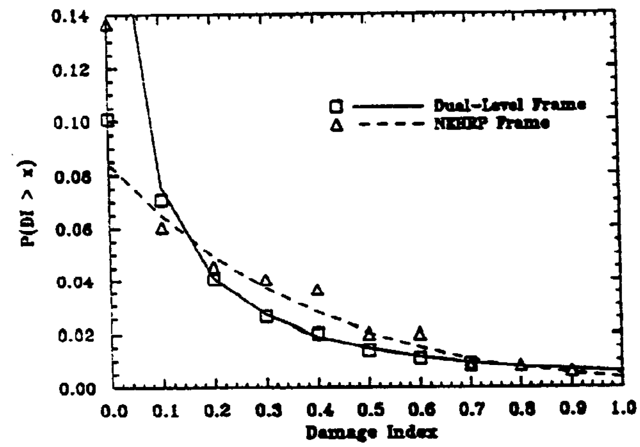

Figure 5: Probability of Exceedance for Damage Indices

Although the points shown in figure 5 calculated using equation 3 for the Dual-level frame (i.e. the squares) remain almost entirely below the points for the NEHRP frame (i.e. the triangles), the fitted extreme value distributions indicate that the Dual-level frame exhibits a lower probability of exceedance than the NEHRP frame only for 0.15 < DI < 0.75. However, since the generalized extreme value distribution is fitted to the tail region, these distributions should not be used to imply the reliability of the frames for small damage indices. Furthermore, none of the Northridge records result in a damage index large enough to exceed a threshold of DI = 0.8 for the Dual-level frame and DI = 1.0 for the NEHRP frame. Therefore, no data for damage indices above these threshold values were included in the fitting of the extreme value distributions, and thus, the fitted distributions should be used with caution when evaluating the reliability of the Dual-level and NEHRP frames above DI = 0.8 and DI =1.0, respectively.

The probabilities of exceedance, considering the effect of epicentral distance, for the global drifts (roof displacement / building height) are shown in figure 6. The probability of exceedance for the Dual-level frame is consistently below the probability of exceedance for the NEHRP frame, indicating that the Dual-level frame is a better design if the engineer wishes to limit the global drift of the structure. Once again, the extreme value distributions should not be used to imply the reliability of the frames at very low global drift levels.

The probabilities of exceedance, considering the effect of epicentral distance, for the local drifts (maximum interstory drift) are shown in figure 7. As with the global drifts, the probability of exceedance for the Dual-level frame is consistently above the probability of exceedance for the NEHRP frame, indicating the Dual-level frame is a better design if the engineer wishes to limit the local drift of the structure.

It must be remembered that the calculated reliabilities assume the occurrence of a Northridge type earthquake (i.e. M ≈ 6.7 on a blind thrust fault).

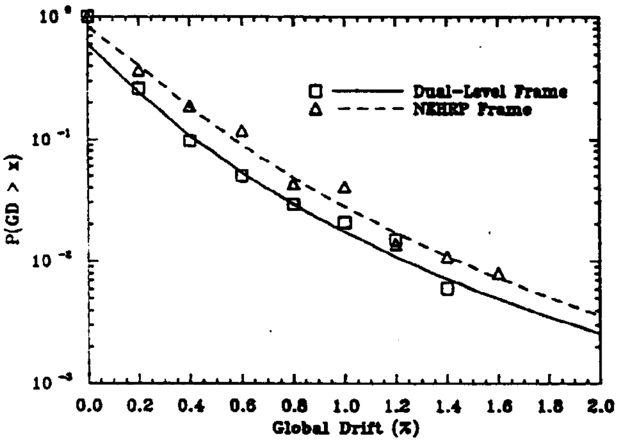

Figure 6: Probability of Exceedance for Global Drift

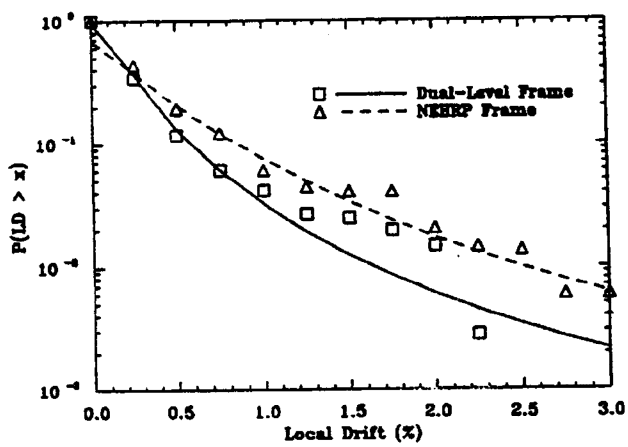

Figure 7: Probability of Exceedance for Local Drift

CONCLUSIONS

The Dual-level design procedure results in better drift control for severe ground motions that force the building into the inelastic range. Thus, excessive structural and non-structural damage may be avoided, and with little or no interruption to the building occupation after the earthquake. Furthermore, under small and moderate ground motions the Dual-level design remains nearly elastic, while under severe ground motions a soft story collapse is avoided; thus, the design comes closer to attaining the desired design philosophy stated in most current building codes.

The reliability (i.e. the probability of not exceeding given response thresholds) of the Dual-level design is consistently higher than the reliability of the NEHRP design for each of the response quantities considered. In other words, for the same probability level, the response or damage index of the Dual-level frame is much smaller than that of the NEHRP frame. It should be noted that these conclusions are based on results from a Northridge type event (i.e. M ≈ 6.7 earthquake on a blind thrust fault).

The calculated risk levels for a future event similar to the Northridge earthquake within a circular area with a radius of 100 km can be summarized as follows:

- The probability of exceeding global drifts of 0.5% and 1.5% are 0.125 and 0.006 for the NEHRP frame and 0.075 and 0.003 for the Dual-level frame, respectively.
- The probability of exceeding local drifts of 0.5% and 2.0% are 0.2 and 0.018 for the NEHRP frame and 0.15 and 0.006 for the Dual-level frame, respectively.

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