IMPLICATIONS OF A PROPORTIONING METHOD FOR EARTHQUAKE-RESISTANT RC FRAMES SUBJECTED TO STRONG GROUND MOTION

JoAnn P BROWNING[1]

SUMMARY

This paper considers the application of a simple proportioning procedure for earthquake-resistant reinforced concrete frames to provide various levels of target performance objectives. The performance objective is defined by a maximum allowable drift criterion and the assumption that adequate detailing will be provided to allow a ductile response. A series of reinforced concrete frames were proportioned using two levels of performance criteria and the responses to a suite of scaled ground motions are calculated. Results of the study indicate that a target-period criterion can be used to limit the expected drift of reinforced concrete frames during a design-level event. Furthermore, the required member proportions determined using the proposed procedure can be used to select a structural configuration that will limit drift while providing a solution that is feasible for economic and architectural considerations.

INTRODUCTION

The focus of this paper is on the application of a simple period criterion to provide different levels of expected structural performance during a design-level earthquake event. A simple method was developed to proportion earthquake-resistant reinforced concrete building frames that requires only the original structural configuration and a simplified displacement response spectrum for the level of expected demand [Browning, 1998]. The method is attractive because it separates ideas of stiffness-requirements for resisting lateral loads from strength-requirements for resisting gravity loads. By selecting appropriate structural dimensions to satisfy a period criterion, the maximum drift is limited and the amount of expected damage is reduced. This procedure provides a simple way to limit drift so that more efforts can be made to provide proper detailing of all elements for reaching the target deformations without brittle failure.

The proposed method is used as a design tool to provide an expected level of performance for a given displacement demand. If the expected performance of a structure is defined in terms of allowable drift, then satisfying the performance criteria can be accomplished by providing appropriate stiffness in combination with proper detailing for a ductile response. This paper highlights some implications of using the proposed proportioning procedure to define a level of expected performance for reinforced concrete frames for a region of high seismicity. A series of analytical frames were proportioned using the proposed method for two levels of performance, both aimed at preventing structural damage but differing in the expected level of non-structural damage. Once proportioned, an estimate of the displacement response was calculated using a suite of scaled ground motions.

PROPORTIONING METHOD

A brief description of the proposed proportioning method is given to provide a basis for evaluating the relative performance of a series of analytical frames. A detailed description of the formulation and analytical evaluation of the method can be found in Browning [1998].

The basis for the proportioning method is derived from work completed by Shimazaki [1988] and Lepage [1997]. Shimazaki showed that an upper-bound level of drift for a reinforced concrete system could be

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[1] *Department of Civil & Environmental Engineering: University of Kansas, USA*

estimated using a smooth displacement response spectrum and a modified system period equal to the fundamental period of vibration of the system multiplied by $\sqrt{2}$. This method worked well for systems with initial periods exceeding the characteristic period of the ground motion (T_g, the period at the intersection of the nearly-constant acceleration range of response and the nearly-constant velocity range of response). The displacement response of systems with initial periods less than T_g were not bounded by the smooth response spectrum because of the influence of strength. In later research, Lepage [1997] found that if a simplified displacement response spectrum was used, one that remained linear following the slope of the nearly-constant velocity region of response through the nearly-constant acceleration region of response to the origin (Fig. 1), then an upper bound for displacement response could be determined using the simple method provided by Shimazaki.

A method for proportioning reinforced concrete frame buildings was developed using the ideas presented by Shimazaki [1988] and Lepage [1997]. The maximum expected drift of a reinforced concrete frame for a given event was limited by satisfying a maximum allowable period criterion. Following the form of the simplified spectrum defined by Lepage, a reasonable estimate of displacement demand can be defined as D = 10T for a region of high seismicity (Fig. 1), where D is the displacement demand in inches and T is the modified period of the system in seconds. Therefore, the target-period criterion can be expressed as:

$$T_i \leq \frac{R_L \cdot H}{10 \cdot \sqrt{2} \cdot F_p} \quad (1)$$

where R_L is the limiting maximum drift ratio (ratio of total drift to total building height), T_i is the initial period of the system (sec), H is the total height (in.), and F_p is the participation factor for the mode considered. This procedure was tested using a series of analytical reinforced concrete frames ranging from 5 to 17 stories, and having varied bay widths, varied story heights, and column stiffnesses [Browning, 1998]. The case of a regular frame with a tall first story (30% taller than other stories) also was investigated. Results of the study showed that the maximum total-drift and maximum story-drift could be limited using the target period criterion.

EXAMPLE FRAMES

The procedure described above can be used to proportion frames for general performance objectives defined by a maximum allowable drift. A series of five reinforced concrete frames were proportioned using two maximum drift criteria to illustrate possible design scenarios. Once the target drift criterion is satisfied, adequate reinforcement for shear and bond considerations must be provided so that the target drift can be obtained without brittle failure occurring in any element.

The selected frame configurations had three square bays with dimensions of 30-ft. and ranged from 5 to 13 stories in two-story increments. The story heights were regular with dimensions of 10-ft.. The concrete was assumed to have a compressive strength, f'_c, of 4000 psi with an average modulus of elasticity of 4000 ksi. The reinforcing steel was assumed to have a yield stress of 60 ksi. The total girder depths were selected as one-twelfth the span length with average reinforcement ratios of 0.75%. The girder width was assumed to be one-half of the total depth. Square column dimensions were selected to satisfy the target-period criterion using a loading considered effective on the building during response to strong ground motion of 200 psf.

To illustrate the effectiveness of the proposed method for a general performance criteria, a maximum allowable drift equal to 1.5% of the total building height was specified. A building with proper detailing at this level of response would be expected to satisfy a performance category without structural damage and with limited non-structural damage. A maximum story-drift ratio (SDR, ratio of maximum story drift to story height) of 2.0% would be expected for regular frames with a maximum mean-drift ratio (MDR, ratio of calculated total drift to total building height) of 1.5%. This level of drift represents a reasonable limit for the distortion that would render the non-structural elements of the building a total loss.

Column proportions were selected to satisfy the criterion defined by Eq. 1 with a maximum allowable mean-drift ratio of 1.5%. The resulting square column dimensions are shown in Table 1 and range from 30-in. square columns for a 5-story frame, to 36-in. square columns for a 13-story frame. These dimensions were found to be similar to dimensions of columns in existing reinforced concrete frames found in regions of high seismcity, such as in western U.S. [Browning, 1998]. The frame periods also were found to be consistent with periods estimated for existing reinforced concrete building frames [Goel and Chopra, 1997].

It is of interest to estimate a level of response for the proportioned frames when subjected to ground motion that has been scaled to be representative of the specified displacement demand, D = 10T. To accomplish this task, a suite of ground motions was used to calculate the nonlinear dynamic responses of the proportioned frames. The ground motions were previously selected and scaled so that the calculated displacement response spectra would fill the displacement demand curve for a range of building periods up to 3.0 sec [Browning, 1998]. The earthquakes represent a variety of geographic locations and site conditions that are documented in the referenced work. The displacement response spectra for the scaled motions are shown in Fig. 2. It is noted that in the period range around 1.0 sec, the displacement demand exceeds the target demand curve. This exceedence was necessary in order to fill the range of building response periods with representative displacement demand.

A nonlinear dynamic analysis program developed by Otani [1974] and later modified by Saiidi [1979a, 1979b] and Lopez [1988] was used to calculate the responses of the frames to the scaled ground motions. Previous studies that used the program to calculate responses of experimental and existing reinforced concrete structures to strong ground motion have demonstrated good results [Saiidi, 1979b; Eberhard, 1989; Lopez, 1988; Lepage, 1997; Browning et al., 1997]. Deformations for all members were defined for the program using the tri-linear moment-curvature relationship shown in Fig. 3 that includes points associated with cracking and yield, and has a 0.1% post-yield stiffness. Initial stiffnesses for all members were determined using gross sectional properties. The girder stiffnesses were calculated with a factor of two to account for the stiffness contribution of the slab. The cracking moment capacity for all members was calculated using a modulus of rupture of $7.5\sqrt{f'_c}$. The moment capacity at yield was equivalent to the nominal moment capacity calculated using a stress-strain relationship for the concrete defined by Hognestad [1951] with a maximum compressive strain of 0.004. Hysteresis in the elements was defined using the rules specified by Takeda [1970] with an unloading slope coefficient of 0.4. A reinforcement ratio of 1.0% was selected for all columns.

Additional deformations due to slip of the reinforcement and second-order effects (P-Δ) were included in the analysis routine [Saiidi, 1979a, 1979b]. The slip rotation at yield of the reinforcement was estimated for developing the full yield stress in the steel with a uniform bond stress of $6\sqrt{f'_c}$. A damping coefficient of 2.0% of critical damping was assumed in the analyses.

Results of the analyses shown in Figs. 4 and 5 are represented by the solid symbols and lines. The maximum mean-drift ratios calculated for all input ground motions, shown in Fig. 4, were less than the target limit of 1.5%. The frames with five and seven stories had maximum total drifts that were close to the limit, but the maximum drift decreased for the frames with increasing number of stories. This trend was the result of the periods of the systems exceeding the largest displacement demand region of response.

Figure 5 shows the maximum story-drift ratios that were calculated for each story during the response to all ground motions. The solid vertical line in the figures represents the maximum calculated mean-drift ratio for all input ground motions. The performance of the frames satisfied the intended objective with maximum total drifts that were less than 1.5% of the total height of the structures and having maximum story-drifts that were approximately 2.0% of the total story heights. It is interesting to note that although the mean-drift ratio decreased with increasing number of stories, the maximum story-drift ratio reached 2.0% for every frame.

ALTERNATE PERFORMANCE OBJECTIVE

A more stringent performance criterion was considered by limiting the maximum allowable drift to 1.0% of the total height of the structure. The new limitation would decrease the maximum distortion and decrease the expected level of damage. At this level of drift, the frames would likely have nonlinear response and proper detailing for shear and bond demands must be provided in order to protect the integrity of the structure.

The columns of the frames described in the previous section were re-proportioned according to the criteria defined by Eq. 1 with R_L =1.0%. The resulting target periods, initial periods, and square-column dimensions are listed in Table 2. The square column dimensions ranged from 56-in. for the 5-story frame to 70-in. for the 13-story frame. Clearly, the dimensions required to limit the maximum expected drift to 1.0% of the total height of the structure are not economically feasible. The resulting structural configuration is more like a building with slender walls than a frame.

One solution to satisfy the target-period criterion with reasonable column dimensions is to increase the total girder depths to one-tenth the span length. The width proportion and the reinforcement ratios were not changed. The required square-column dimensions to satisfy the target-period criterion were reduced dramatically as shown in Table 2. These column dimensions, although larger than the original frames described in Table 1, represent a possible solution for the higher-performance criterion.

The nonlinear response of the frames with column dimensions listed in Table 2 and girder-depths of one-tenth the span length were calculated using the scaled ground motions to test the hypothesis that limiting the initial period of the frame will limit the drift in a predictable manner. The results of the analyses are shown in Fig. 4 and Fig. 5 as the hollow symbols and dotted lines. The responses of 46 out of the 50 analyses remained within the prescribed maximum mean-drift ratio limit of 1.0%. Because the initial periods of the frames were less than 1.0 sec, all of the frames experienced the high drift demands indicated in Fig. 2 around the one-second period range. As a result, all of the frames had maximum mean-drift ratios that were close in value to the 1.0% limit. The four analyses that exceed the 1.0% limit were in response to the Kobe, Seattle, and Sendai records, all of which exceeded the design spectrum in the short-period range.

Perhaps a better indication of the improved performance of the re-proportioned frames are the calculated story-drift ratios (Fig.5). The maximum story-drift ratios that were calculated for all frames subjected to the ten ground motions did not exceed 1.5%. The larger girder and column proportions promoted a decrease in the distortion in the bottom-half of the frames with five and seven stories, whereas the top-half of the frames with more than seven stories experienced less distortion than the original frames.

It is of interest to consider another solution to satisfy the target-period criterion for a maximum mean-drift ratio of 1.0% by providing walls in the system. Consider five reinforced concrete frames similar to those described in the initial analyses but with column dimensions determined using a simple gravity-load criterion of a maximum axial stress equal to 0.45 f'_c. The resulting column dimensions are listed in Table 3. An 8-in. wall was added to the interior bay, using the interior columns as boundary elements, to form a wall-frame system. This wall-frame system can support two additional regular reinforced concrete frames and satisfy the target-period criterion as indicated in Table 3. The limiting concern for this type of system becomes providing adequate detailing for large shear stresses and accounting for the contribution of shear deformations to the total building response.

CONCLUSIONS

The simple target-period criterion can be used to proportion earthquake-resistant reinforced concrete frames for various levels of intended performance based on drift limitations and proper detailing. For average performance levels, such as a maximum expected drift of 1.5% of the total height of the structure, the required column dimensions to satisfy the criterion are similar to the dimensions of existing reinforced concrete columns in regions of high seismicity. To provide a limited maximum expected drift of 1.0% of the total building height, alternative structural configurations are necessary. Increasing the girder depths or introducing a wall-element into the system can satisfy this criterion. For the frames considered in this study, limiting the drift of the frames with less than ten stories to a maximum mean-drift ratio of 1.0% was less successful than limiting the ratio to 1.5% because of the higher drift demands in the short-period range.

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APPENDIX

Unit Conversion:

1 ft = 305 mm

1 in. = 25.4 mm

1 ksi = 6.89 MPa

1 psi = 6.89 kPa

Table 1 Column Dimensions to Satisfy R_L = 1.5% Criterion

Number of Stories	Target Frame Period (sec)	Initial Frame Period (sec)	Square Column Dimension (in.)
5	0.51	0.52	30
7	0.71	0.73	30
9	0.92	0.95	30
11	1.12	1.13	32
13	1.32	1.28	36

Table 2 Column Dimensions to Satisfy R_L = 1.0% Criterion

Number of Stories	Target Frame Period (sec)	Girder Depth = Span / 12		Girder Depth = Span / 10	
		Initial Period (sec)	Column Width (in.)	Initial Period (sec)	Column Width (in.)
5	0.34	0.34	56	0.34	40
7	0.48	0.47	60	0.47	42
9	0.61	0.60	64	0.61	42
11	0.75	0.75	66	0.75	44
13	0.88	0.87	70	0.88	44

Table 3 Periods of Wall-Frame Systems with 3 Frames

Number of Stories	Target Period (sec)	Gravity-Load Column Width (in.)	Period of Wall-Frame System (1 wall-frame + 2 frames) (sec)
5	0.34	24	0.30
7	0.48	28	0.44
9	0.61	30	0.59
11	0.75	34	0.72
13	0.88	36	0.87

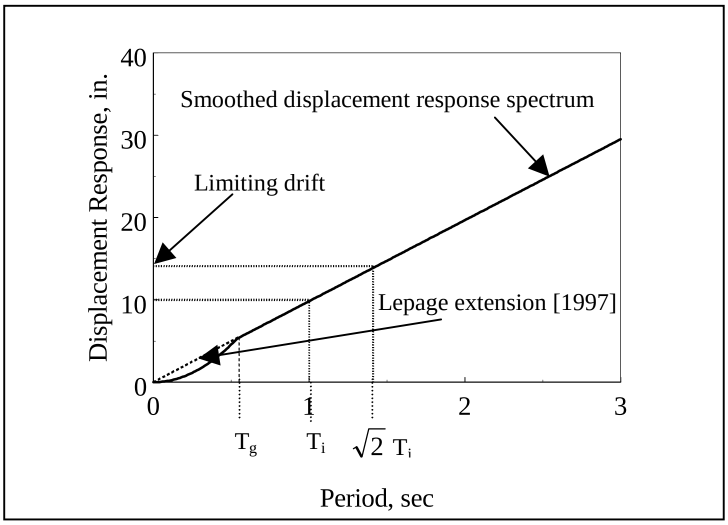

Fig. 1 Upper Bound Estimate for Maximum Drift

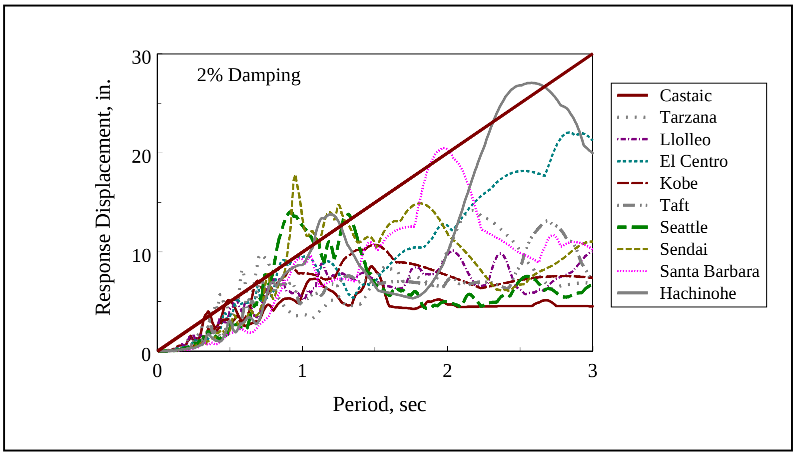

Fig. 2 Displacement Response Spectra for Scaled Ground Motions

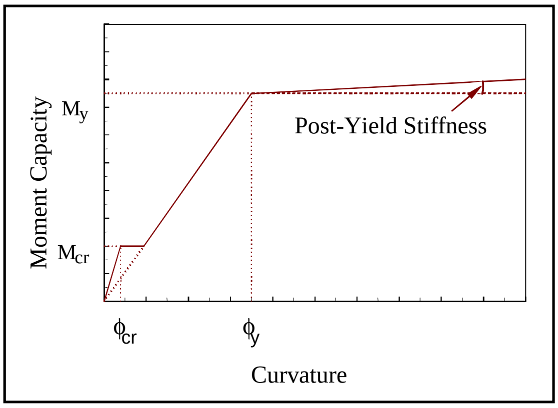

Fig. 3 Moment-Curvature Relationship for Analyses

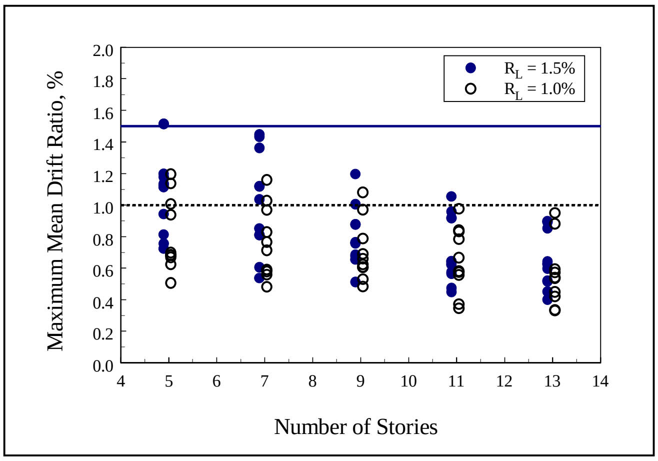

Fig. 4 Maximum Calculated Mean-Drift Ratios

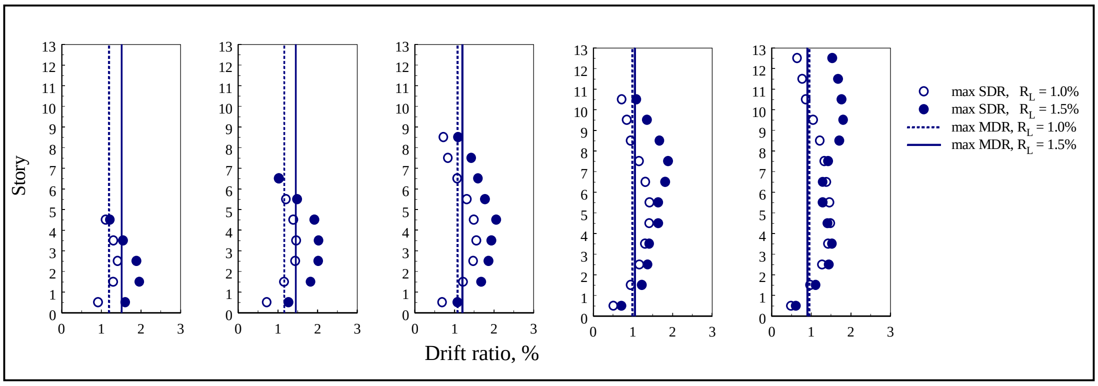

Fig. 5 Maximum Story-Drift Ratios for All Ground Motions with Maximum Mean-Drift Ratio