Relating the Seismic Drift Demands of SMRFs to Element Deformation Demands

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A procedure is outlined and evaluated for estimation of beam and panel zone deformation demands for given estimates of story drift demands for regular steel moment resisting frame (SMRF) structures. The total story drift demand is related to the story plastic drift demand by estimating the story yield drift based on the weakest element at the connection. The story plastic drift demand is related to the panel zone and beam plastic deformation demands by a function based on story geometry and member properties. The procedure is verified for a series of code compliant SMRFs. It complements a process presented in the literature that permits the estimation of seismic drift demand for frame structures from the spectral displacement demand at the first mode period of the structure. The combined process should prove useful in conceptual design, in estimating deformation demands for performance assessment, and in improving basic understanding of seismic behavior of steel frame structures.

INTRODUCTION

The recent emphasis on performance-based engineering coupled with the emphasis on deformation-based seismic design necessitates the ability to predict global (e.g., roof), intermediate (e.g., story) and local (element) deformation demands. While nonlinear dynamic analysis of accurate models subjected to sets of ground motion time histories remains the best option for estimation of seismic demands, the effort inherent in such a process is often not warranted. A simplified demand estimation process that provides reasonable estimates of the demands will assist in conceptual design by providing targets of structure strength and stiffness, preliminary selection of member sizes and choice of connection types for the structure. Performance evaluation of structures will be assisted as quick, reasonable estimates of demands will be available, and indications will be provided whether additional effort is required for detailed structural demand evaluation.

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The estimation of seismic drift demands for frame structures has been the subject of much research (e.g., Fajfar and Fischinger, 1988; Nassar and Krawinkler, 1991, 1997; Wen and Han, 1997; Miranda, 1997; FEMA, 1997; Gupta and Krawinkler, 2000a). Most of these studies focused on developing relationships between a spectral quantity (i.e., the spectral displacement at the first mode period of the structure) and structural deformation quantities such as roof and story drift demands. This study extends these relationships to relate story drift demands to elements plastic deformation demands. Thus, as outlined in Figure 1, a complete loop is developed between the spectral displacement demand and element plastic deformation demands using a series of modification factors and functions. The first four modification factors identified in Figure 1, which relate the spectral deformation demand to story drift demands, are briefly summarized in the next section. The development of these modification factors is described in detail in Gupta and Krawinkler (2000a). This paper focuses on the relationship between story drift demand and element plastic deformation demands, which is verified for a series of code compliant steel moment-resisting frame (SMRF) structures. Plan views and elevations for these structures, which were designed as part of the SAC steel program, are shown in Figure 2. Details pertaining to the structures, analytical modeling, and ground motions used are given in Gupta and Krawinkler (1999).

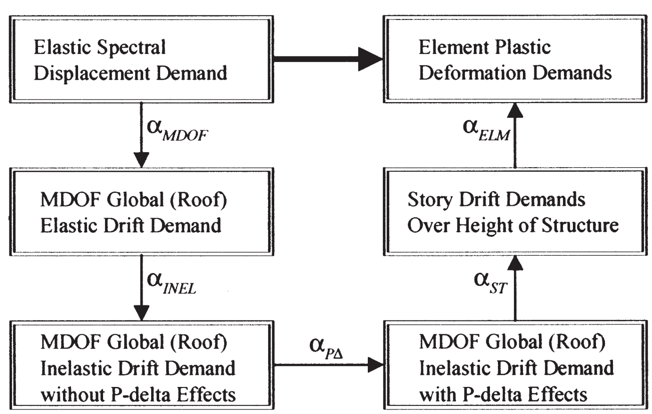

Fig. 1. Framework for simplified demand estimation procedure.

GROUND MOTION SEISMIC DRIFT DEMAND RELATIONSHIPS

The modification of the spectral displacement demand at the first mode period of the structure to the story drift demands is carried out through the use of four modification factors, which are statistically derived from extensive linear and nonlinear dynamic analyses of the model structures. The development of these modification factors is described in detail in Gupta and Krawinkler (2000a). Results of the referenced study are summarized below:

MDOF modification factor, α_{MDOF}: This factor transforms the elastic spectral displacement demand at the first mode period of the structure to the roof elastic drift demand of the multi-degree-of-freedom (MDOF) structure, neglecting P-delta effects. A good estimate of this factor is the first mode participation factor PF_1 unless higher mode spectral displacements are unusually large. For structures with a period exceeding about 2 seconds it is advisable to use $1.1 \times PF_1$ to account for some higher mode contribution. For ground motions with large higher mode spectral displacements, e.g., eastern U.S. ground motions; the modification factor should be obtained from an elastic modal analysis as it may significantly exceed the PF_1 value.

Inelasticity modification factor, α_{INEL}: This factor transforms the roof elastic drift demand to the roof inelastic drift demand, neglecting P-delta effects. The median value of this factor for regular structures with a period longer than 1.0 second is estimated to be between 0.7 and 0.8, if significant inelastic behavior is expected. Conservative values for this factor also can be based on single-degree-of-freedom (SDOF) analysis. For periods shorter than about 0.6 seconds the inelasticity modification factor is strongly dependent on both period and level of inelasticity in the structure.

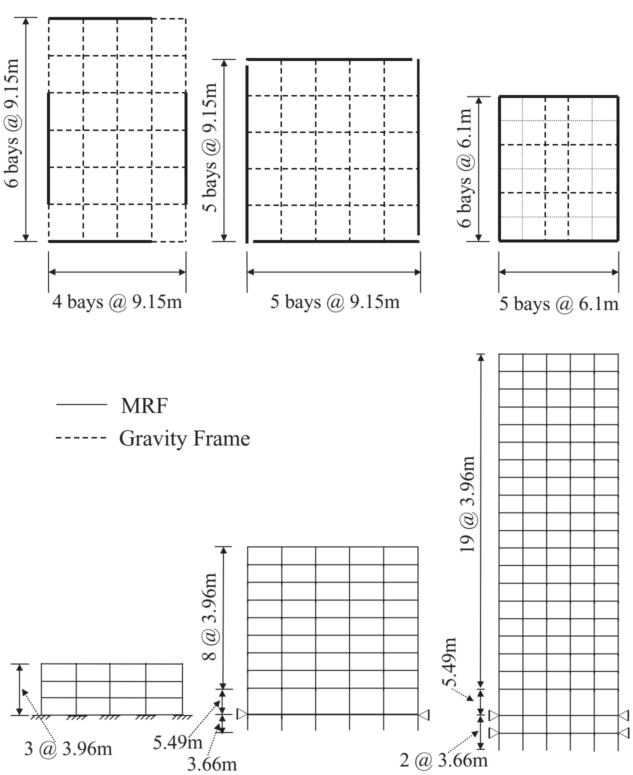

Fig. 2. Plan views and elevations of model buildings.

P-delta modification factor, $\alpha_{P\Delta}$: This factor transforms the inelastic roof drift demand to include structure P-delta effects. The effect of structure P-delta on the response of flexible steel structures has been discussed in detail in Gupta and Krawinkler (2000b). The conclusion from the referenced study is that the P-delta effect is relatively benign unless the ground motion drives the structure into a range of negative post yield stiffness. If the negative stiffness region is entered, only an inelastic time history analysis will indicate the drift amplification due to P-delta. If the design is controlled such that the structure does not reach the negative post yield stiffness region in the displacement range of interest, then the factor may be estimated as $1/(1-\theta)$, where θ is the maximum elastic story stability coefficient (FEMA, 1997).

Story Drift modification factor, α_{ST}: This factor relates individual story drift demands to the roof drift demand. Of primary interest is the largest story drift modification factor, which is the ratio of the maximum story drift over the height of the structure to the roof drift. For regular structures, it is found to be small for low-rise structures (on the order of 1.2), about 2.0 for mid-rise structures, and in the range of 2.5 to 3.0 for tall structures. The modification factor is significantly larger for structures in a location where the response is dominated by higher modes.

The distribution of story drift demands over the height of the structure is found to be dependent on configuration, design decisions, and on the ground motion characteristics, with no unique patterns being evident.

In summary, the maximum story drift demand for an inelastic MDOF structure in which the P-delta sensitive range is avoided can be estimated as follows:

$$\theta_{i,ST,\max} = \alpha_{MDOF} \times \alpha_{INEL} \times \alpha_{P\Delta} \times \alpha_{ST} \left(S_d / H \right) \qquad (1)$$

where S_d, is the spectral displacement demand at the first mode period of the structure and H is the height of the structure.

The assumptions and conditions under which these factors have been developed are discussed in Gupta and Krawinkler (2000a). In general, these factors are believed to be applicable for regular steel moment frame structures whose roof displacement is not greatly affected by higher modes, and which are subjected to ground motion records of the types used in the referenced study (i.e., no significant near field or soft soil effects).

STORY DRIFT   ELEMENT DEFORMATIONS RELATIONSHIP

The estimation of element deformation demands constitutes the final step of the loop shown in Figure 1. The transformation of the story drift demand to the element plastic deformation demands at each floor level is carried out in two steps. First, the story plastic deformation demand is estimated and then this story plastic deformation demand is related to the elements (panel zone, beams) plastic deformation demands.

Estimation of Story Plastic Drift Demand

The story plastic drift demand is determined by subtracting the story yield drift from the total story drift demand. An estimate of the story yield drift is greatly facilitated if the following simplifying assumptions on *elastic* behavior are made:

The inflection points are at mid-heights of the columns and mid-spans of the beams. This is a reasonable assumption for structures that do not have a severe stiffness discontinuity between adjacent stories.

The story yield drift is associated with yielding in beams or panel zones, i.e., at every connection the columns are stronger than the beams and the panel zone. It is assumed that the strong-column criterion is followed.

The effects of gravity loading on yielding in beams and panel zones can be neglected. This is a reasonable assumption for perimeter frames in high seismic areas where the gravity load moments usually constitute only a small percentage of the beam bending strength.

The story elevation has regular geometry and uniform section properties (i.e., the standard portal method assumption can be made).

Lateral deflection due to axial column deformations can be neglected.

For cases in which these assumptions hold, the story yield drift is not expected to be significantly different between adjacent stories, and the substructure shown in Figure 3 represents all essential behavior aspects. The story yield drift can then be estimated as follows:

Step 1: The assumption is made that the beams framing into the subassembly shown in Figure 3 are the first elements to yield at the connection. The shear force in the columns, V_{col}, can then be estimated, using the assumption of midpoint inflection points, by the following equation:

$$V_{col} = \frac{\Delta M}{h\left[1-\frac{d_c}{l}\right]} = \frac{2\times M_{pb}}{h\left[1-\frac{d_c}{l}\right]} \tag{2}$$

where M_{pb} is the beam bending strength, d_c is the depth of the column, h is the height between the two inflection points in the columns, and l is the distance between the inflection points in the beams framing into the connection. (For exterior column lines the factor 2 in the numerator does not exist.)

Using this estimate for the shear force in the column, the shear force in the panel zone can be obtained as:

$$V_{pz} = \left(\frac{2\times M_{pb}}{d_b} - V_{col}\right) \tag{3}$$

This panel zone shear force demand is compared to the panel zone yield strength, $V_{y,pz}$, which is computed as:

$$V_{y,pz} = \frac{F_y}{\sqrt{3}} A_{eff} = \frac{F_y}{\sqrt{3}}(0.95\, d_c\, t_p) \approx 0.55\, F_y\, d_c\, t_p \tag{4}$$

where

F_y = yield strength of the column material

A_{eff} = effective shear area

t_p = thickness of the web including any doubler plates

If the demand computed using Equation 3 is less than the yield strength computed using Equation 4 then the assumption made at the beginning of Step 1 holds true. If not, then the panel zone yields before the beams and the shear force in the column is estimated as:

$$V_{col} = \frac{V_{y,pz}}{\frac{1}{d_b}\left[h\left(1-\frac{d_c}{l}\right)\right]-1} \tag{5}$$

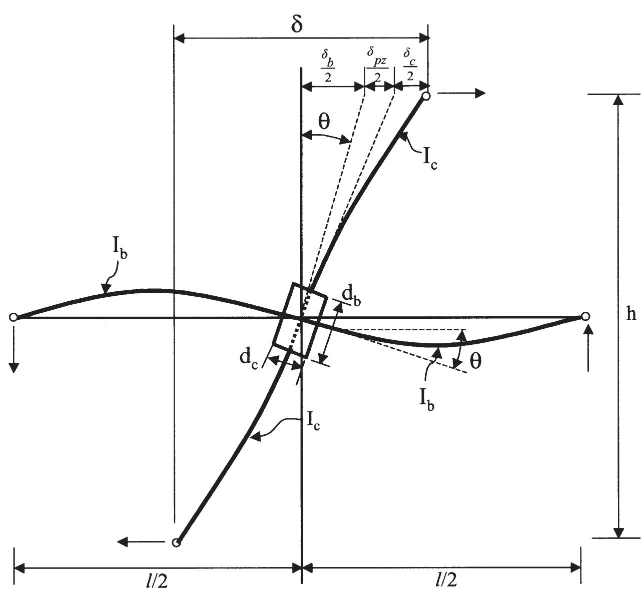

Fig. 3. Components of lateral deflection in beam-column assembly.

Thus, at the end of Step 1, the shear force in the column, V_{col}, associated with first yielding at the connection, has been determined. It should be checked that this value of V_{col} does not result in plastification of the column, i.e., the strong-column criterion is not invalidated.

Step 2: Using the subassembly geometry shown in Figure 3, basic element properties, and the estimated shear force in the column, the associated elastic drift in the elements can be computed. The drift components from the beams, δ_b, from the columns, δ_c, and from the panel zone, δ_{pz}, are computed as:

$$\delta_b = \frac{1}{2} \times \frac{V_{col} \times h^2 \left(1 - \frac{d_c}{l}\right)}{\left(\frac{6EI_b}{l - d_c}\right)} \tag{6}$$

$$\delta_c = V_{col} \times \frac{\left(h - d_b\right)^3}{12EI_c} \tag{7}$$

$$\delta_{pz} = V_{col} \times \frac{\left(h - d_b\right) \times \left(\frac{h}{d_b} - 1\right)}{Gt_p d_c} \tag{8}$$

where

I_b and I_c = moment of inertia for the beams and columns, respectively
d_b = depth of the beam section
E = elastic modulus of steel
G = shear modulus of steel

The story yield drift angle (drift at yield normalized by story height), $\theta_{y,st}$, and consequently the story plastic deformation angle, $\theta_{p,st}$ can be evaluated as:

$$\theta_{y,st} = \frac{\left(\delta_b + \delta_c + \delta_{pz}\right)}{h}$$

and (9)

$$\theta_{p,st} = \theta_{total,st} - \theta_{y,st}$$

The set of equations given above can easily be modified for cases in which the beam sections framing into the connection may not be the same on either side of the connection. For cases in which the plastification in the beam is away from the column face (e.g., in connections with cover-plates, reduced beam section connections, etc.) the M_{pb} values in Equations 2 and 3 need to be amplified to reflect the moment at the column face. Using this procedure for the cases in which the assumptions made previously are valid, a good estimate for the story yield drift and story plastic drift can be obtained.

Relating Story and Element Plastic Deformation Demands

The distribution of element plastic deformation demands as a function of the story plastic drift demand can be estimated using a procedure similar to that adopted for estimating the story yield drift. The process works on the premise given by the following equation (again, the possibility of plastic hinging in the columns is neglected):

$$h \times \theta_{p,st} = h \times \theta_{p,b} + \left(h - d_b\right) \times \theta_{p,pz} \tag{10}$$

where p denotes plastic deformation, b denotes the beam, pz the panel zone, and st the story. The plastic deformation in the beam is assumed to be at the column face. For cases in which the plastification in the beam is away from the column face, $\theta_{p,b}$ should be modified to represent equivalent plastic rotation at the column face.

The initial assumption is made that plastic deformation is present in both the beams and the panel zone. The moment in the beam, M_b, can be written as:

$$M_b = M_{pb} + \alpha\left(\frac{6EI_b}{l}\right) \times \theta_{p,b} \tag{11}$$

where

M_{pb} = beam plastic moment
α = strain-hardening in the moment-rotation relationship

Substituting the value of M_b from Equation 11 for M_{pb} into Equation 2, the shear force in the column is estimated. The panel zone shear force demand is then evaluated as the following:

$$V_{pz} = 2 \times M_b \left[\frac{1}{d_b} - \frac{1}{h\left(1 - \frac{d_c}{l}\right)}\right] \tag{12}$$

V_{pz} is then related to the panel zone yield shear force, $V_{y,pz}$, and the panel zone plastic shear distortion using the following equation:

$$V_{pz} = V_{y,pz} + \beta K_{pz} \theta_{p,pz} \tag{13}$$

where

K_{pz} = $0.95 d_c t_p G$
β = $\frac{b_{cf} t_{cf}^{\,2}}{d_b d_c t_p}$
b_{cf} = breadth of the column flange
t_{cf} = thickness of the column flange

β denotes the strain-hardening for the second slope of the trilinear shear force shear distortion relationship [based on the panel zone model defined by Krawinkler (1978); see Figure 4], K_{pz} is the panel zone elastic shear stiffness, and $\theta_{p,pz}$ is the panel zone plastic shear distortion. The value of β should be adjusted accordingly if any other panel zone model is used. Equating Equations 12 and 13 and eliminating V_{pz} results in the following expression for the panel zone plastic shear distortion as a function of the beam moment:

$$\theta_{p,pz} = \frac{2 \times M_b \left[\frac{1}{d_b} - \frac{1}{h\left(1 - \frac{d_c}{l}\right)} \right] - V_{y,pz}}{\beta K_{pz}} \tag{14}$$

Substituting Equation 14 into Equation 10 and rearranging the terms yields the following expression for the beam plastic deformation demand as a function of the story plastic drift demand:

$$\theta_{p,b} = \frac{\theta_{p,st} \times \beta K_{pz} \left(\frac{h}{h - d_b} \right) - 2 \times M_{pb} \left[\frac{1}{d_b} - \frac{1}{h\left(1 - \frac{d_c}{l}\right)} \right] + V_{y,pz}}{2 \times \alpha \left(\frac{6EI_b}{l} \right) \times \left[\frac{1}{d_b} - \frac{1}{h\left(1 - \frac{d_c}{l}\right)} \right] + \beta K_{pz} \left(\frac{h}{h - d_b} \right)} \tag{15}$$

Once $\theta_{p,b}$ has been determined, $\theta_{p,pz}$ can be determined using Equation 10, and the force demands for the elements can be computed.

The procedure outlined through Equations 2 to 15 permits the estimation of the element plastic deformation demands from the story drift demand. Two special conditions need to be addressed in the proposed procedure:

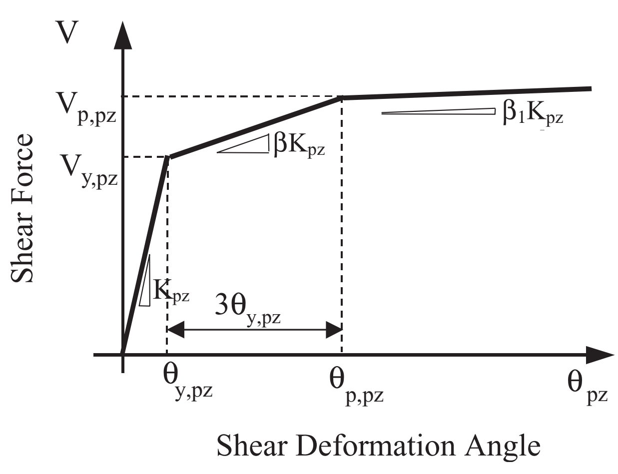

Fig. 4. Trilinear Shear Force-Shear Distortion Relationship. (Krawinkler, 1978)

If only one element is yielding at the connection, then Equation 15 (or following up with Equation 10) will result in the plastic deformation demand estimate for the other element being negative. For such cases, Equation 10 provides a complete solution with the value of the non-yielding element being set to zero.

If a trilinear form of the shear force shear distortion relationship is used for the panel zones (of the type shown in Figure 4), then Equation 13 needs to be modified for cases in which the panel zone reaches the third slope of the shear force shear distortion relationship. The modification is as follows:

$$V_{pz} = V_{y,pz} + \left(\beta K_{pz} \times 3\theta_{y,pz}\right) + \left[\beta_1 K_{pz} \times \left(\theta_{p,pz} - 3\theta_{y,pz}\right)\right] \tag{16}$$

where β_1 represents the slope of the third branch of the shear force shear distortion relationship for the panel zone. This equation can then be transformed into the following form similar to Equation 13:

$$V_{pz} = V'_{y,pz} + \beta_1 K_{pz} \theta_{p,pz} \tag{17}$$

where

$$V'_{y,pz} = V_{y,pz} + \left(\beta - \beta_1\right) \times K_{pz} \times 3\theta_{y,pz}$$

Equation 17 replaces Equation 13, the value of $V_{y,pz}$ is changed to $V'_{y,pz}$ and β is replaced by β_1 in Equations 14 and 15.

VALIDATION OF PROCEDURE

The validity of the proposed procedure is tested by comparing estimates of element deformation demands obtained using the simplified procedure to estimates obtained using nonlinear time history analysis. The story drift demands obtained from the time history analysis are used as the starting point for the simplified procedure.

A set of code compliant steel moment resisting frame structures, designed as part of the SAC steel project, is used for the validation process. The plan views and elevations of the structures are shown in Figure 2. The member sections for the 9-story and 20-story structures (designed for Los Angeles conditions) are given in Table 1.

The perimeter moment-resisting frames are modeled as two-dimensional frames with point plastic hinges having bilinear moment-rotation relationships with 3 percent strain hardening. Clear span dimensions are used with panel zones being ascribed a trilinear shear force shear distortion relationship as shown in Figure 4. The structures are subjected to a set of 20 ground motions, which on average represent a hazard level with a 2 percent probability of being exceeded in 50 years (Somerville et al., 1997). Details per-

Table 1. Beam and Column Sections, and Doubler Plate Thickness for 9- and 20-story Model Buildings

9-story Building

Story/Floor	NS Moment Resisting Frames: COLUMNS Exterior	Interior	DOUBLER PLATES (in)	GIRDER	NS Gravity Frames: COLUMNS Below penthouse	Others	BEAMS
9/Roof	W14X233	W14X257	0,0	W24X68	W14X61	W14X48	W16X26
8/9	W14X257, W14X233	W14X283, W14X257	0,0	W27X84	W14X90, W14X61	W14X82, W14X48	W18X35
7/8	W14X257	W14X283	0,0	W30X99	W14X90	W14X82	W18X35
6/7	W14X283, W14X257	W14X370, W14X283	0,0	W36X135	W14X120, W14X90	W14X109, W14X82	W18X35
5/6	W14X283	W14X370	0,0	W36X135	W14X120	W14X109	W18X35
4/5	W14X370, W14X283	W14X455, W14X370	0,0	W36X135	W14X159, W14X120	W14X145, W14X109	W18X35
3/4	W14X370	W14X455	0,0	W36X135	W14X159	W14X145	W18X35
2/3	W14X370, W14X370	W14X500, W14X455	0,0	W36X160	W14X211, W14X159	W14X193, W14X145	W18X35
1/2	W14X370	W14X500	0,0	W36X160	W14X211	W14X193	W18X35
-1/1	W14X370	W14X500	0,0	W36X160	W14X211	W14X193	W21X44

20-story Building

Story/Floor	NS Moment Resisting Frames: COLUMNS Exterior	Interior	DOUBLER PLATES (in)	GIRDER	NS Gravity Frames: COLUMNS	BEAMS 40 feet span	BEAMS 20 feet span
20/Roof	15X15X0.50	W24X84	0,0	W21X50	W14X108, W14X43	W21X44	W12X16
19/20	15X15X0.75, 15X15X0.50	W24X117, W24X84	0,0	W24X62	W14X108	W21X50	W14X22
18/19	15X15X0.75	W24X117	0,5/8	W27X84	W14X108	W21X50	W14X22
17/18	15X15X0.75, 15X15X0.75	W24X131, W24X117	0,5/8	W27X84	W14X176, W14X108	W21X50	W14X22
16/17	15X15X0.75	W24X131	0,5/8	W30X99	W14X176	W21X50	W14X22
15/16	15X15X0.75	W24X131	0,5/8	W30X99	W14X176	W21X50	W14X22
14/15	15X15X1.00, 15X15X0.75	W24X192, W24X131	0,5/8	W30X99	W14X257, W14X176	W21X50	W14X22
13/14	15X15X1.00	W24X192	0,0	W30X99	W14X257	W21X50	W14X22
12/13	15X15X1.00	W24X192	0,0	W30X99	W14X257	W21X50	W14X22
11/12	15X15X1.00, 15X15X1.00	W24X229, W24X192	0,0	W30X99	W14X311, W14X257	W21X50	W14X22
10/11	15X15X1.00	W24X229	0,0	W30X108	W14X311	W21X50	W14X22
9/10	15X15X1.00	W24X229	0,0	W30X108	W14X311	W21X50	W14X22
8/9	15X15X1.00, 15X15X1.00	W24X229, W24X229	0,0	W30X108	W14X370, W14X311	W21X50	W14X22
7/8	15X15X1.00	W24X229	0,0	W30X108	W14X370	W21X50	W14X22
6/7	15X15X1.00	W24X229	0,0	W30X108	W14X370	W21X50	W14X22
5/6	15X15X1.25, 15X15X1.00	W24X335, W24X229	0,0	W30X108	W14X455, W14X370	W21X50	W14X22
4/5	15X15X1.25	W24X335	0,0	W30X99	W14X455	W21X50	W14X22
3/4	15X15X1.25	W24X335	0,0	W30X99	W14X455	W21X50	W14X22
2/3	15X15X2.00, 15X15X1.25	W24X335, W24X335	0,0	W30X99	W14X550, W14X455	W21X50	W14X22
1/2	15X15X2.00	W24X335	0,0	W30X99	W14X550	W21X50	W14X22
-1/1	15X15X2.00	W24X335	0,0	W30X99	W14X550	W24X68	W16X26
-2/-1	15X15X2.00	W24X335	0,0	W14X22	W14X550	W21X50	W14X22

General Notes:

1. For built-up sections, the first two terms signify the outer width and depth of the section, the third term signifies the thickness of the plate, e.g., 15x15x2.00 is a 15-in. square box section formed using 2-in. thick plates.
2. For doubler plate thickness, the first number signifies the value for the exterior column, the second for the interior column.
3. Splices are located 6 ft (1.83m) above the floor centerline in stories where 2 column sections are given (below splice, above splice).

taining to the structures, analytical modeling, and ground motions are given in Gupta and Krawinkler (1999).

The median story drift demands obtained from the time history analysis are used as the starting point. At the floor level, a floor drift angle is calculated as the average of the adjoining two stories drift angles. The story yield and plastic drifts are computed using Equations 2 to 9. The procedure outlined by Equations 10 to 17 is employed to estimate the element plastic deformation demands, which are then compared to the median element plastic deformation demands based on the nonlinear dynamic analysis.

Figure 5 and Figure 6 present comparisons of demands at an interior column line of the 9-story structure. Figure 5 compares the beam plastic rotation demands estimated using the simplified procedure with those obtained from the nonlinear time history analysis. Figure 6 presents a similar comparison for the panel zone plastic shear distortion demands. Both figures also show the floor drift angles obtained from the time history analysis and the yield drift angles computed from the simplified procedure. The estimated demands capture the distribution and absolute values of demands quite well. The validity of the simplified procedure was also evaluated for a 9-story structure employing reduced beam section details. The comparison of estimated and calculated element demands was found to be similar to the comparison for the presented 9-story structure.

The procedure has been developed with several simplifying assumptions, such as no plastification in the columns. This assumption, and other (e.g., midpoint inflection points) assumptions are not valid in all cases. Figure 7 and

Figure 8 present results for the 20-story structure, which undergoes significant inelastic deformations including column plastic hinging. At the median drift demand level the simplified procedure still is able to reasonably capture the distribution of demands between the panel zone and beams. The observed discrepancies arise from the assignment of the plastic deformation resulting from column hinging to the panel zone and/or beams at that floor level, for a few severe ground motions.

Appendix 1 provides an illustrative example for estimating plastic deformation demands in beams and panel zones.

CONCLUSIONS

A simplified procedure is presented that relates story drift demands to element (panel zone and beam) plastic deformation demands. This procedure complements a process described elsewhere (Gupta and Krawinkler, 2000a) that relates estimates of the story drift demands to the spectral displacement at the first mode period of the structure. In combination, the entire process can be used to relate a measure of spectral displacement demand to the element (local), intermediate (story), and roof (global) deformation demands of a regular frame structure.

While the relationship between spectral displacement demand and roof and story drift demands is based on statistically derived modification factors, the relationship between story drift demands and element deformation demands is through functions that are dependent only on the structure s geometric properties and basic element properties. The proposed relationships between story and element deformation demands can be used for most types of fully-

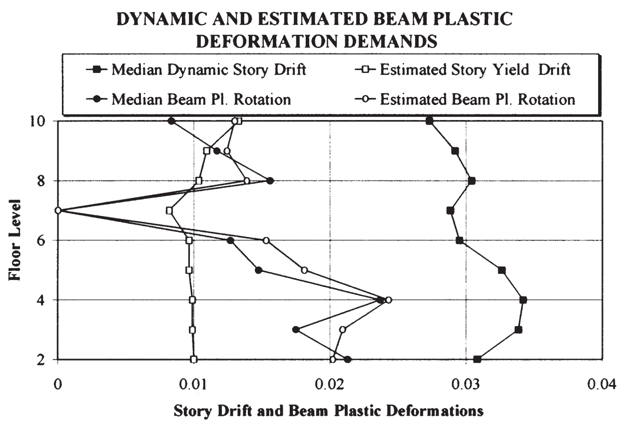

Fig. 5. Comparison of beam plastic deformation demands, dynamic analysis vs. simplified method; 9-story structure.

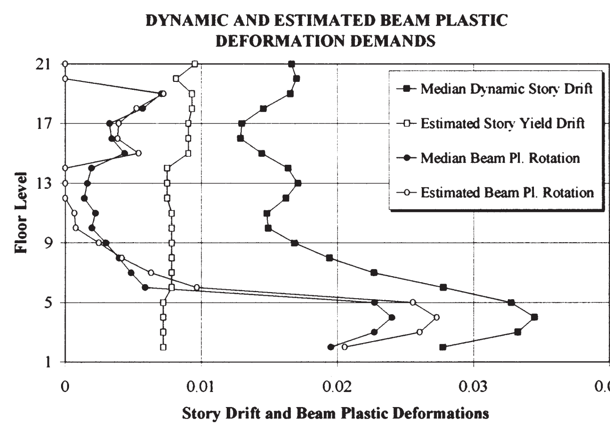

Fig. 7. Comparison of beam plastic deformation demands, dynamic analysis vs. simplified method; 20-story structure.

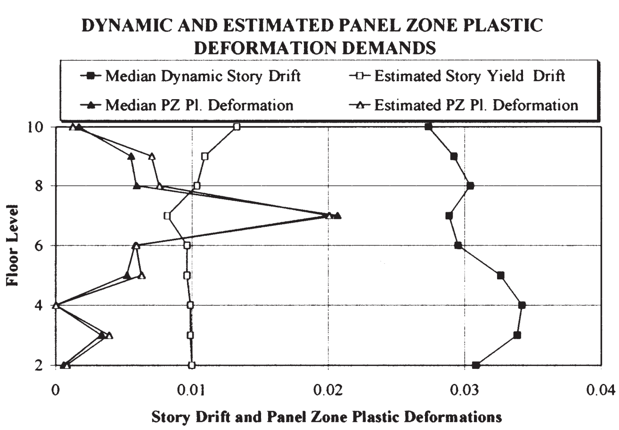

Fig. 6. Comparison of panel zone plastic deformation demands, dynamic analysis vs. simplified method; 9-story structure.

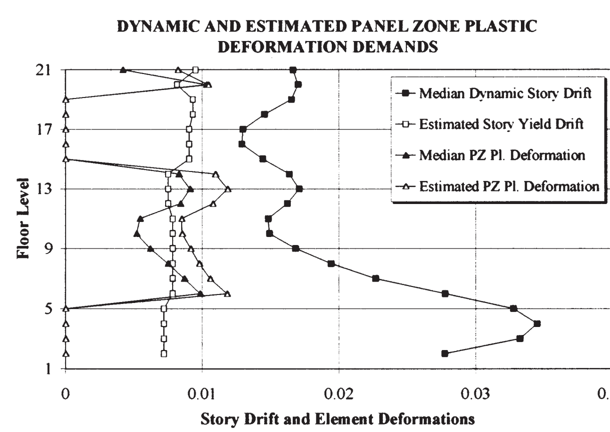

Fig. 8. Comparison of panel zone plastic deformation demands, dynamic analysis vs. simplified method; 20-story structure.

restrained connections such as standard welded beam-to-column connections, connections with cover-plates, reduced beam section connections, and others. The effect of framing in the transverse direction on the panel zone behavior is not considered in this study.

The proposed relationship distributes the story drift demand to the elements at a connection in proportion to their strength and based on interactions governed by the structure s geometric properties using representative substructures. The story yield drift is estimated first, which provides a measure of the story plastic drift demand. This demand is then related to the element plastic deformation demands. The estimation of story yield drift also allows an assessment of the story ductility demand.

The proposed process provides a simple tool for estimating deformation demands, which should prove useful for structural performance evaluation, assistance in conceptual design, and identification of cases in which more refined analysis may be necessary. For regular SMRF structures the developed process should provide reasonable estimates of seismic deformation demands. At different stages of the development, however, simplifying assumptions have been made, which may invalidate demand estimates for structures and ground motions far outside the range of parameters used in this study.

ACKNOWLEDGMENTS

The work forming the basis for this publication was conducted pursuant to a contract with the Federal Emergency Management Agency (FEMA) through the SAC Joint Venture. SAC is a partnership of the Structural Engineers Association of California, the Applied Technology Council, and the California Universities for Research in Earthquake Engineering. The opinions expressed in this paper are those of the authors. No warranty is offered with regard to the results, findings and recommendations contained herein, either by FEMA, the SAC Joint Venture, the individual joint venture partners, their directors, members or employees, or the authors of this publication. These organizations and individuals do not assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any of the information included in this publication.

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APPENDIX

Example Problem

The maximum element plastic deformation demands for a 10-story SMRF structure (each story height is 3.6 m, each bay width is 9 m, T_1 = 1.7 seconds, PF_1 = 1.4) are to be estimated for two seismic hazard levels, one with a 475-year return period and the other with a 2475-year return period. The acceleration spectra for the two hazard levels are defined by 0.5g/T (475-year hazard level) and 1.0g/T (2475-year hazard level), in the vicinity of the first mode period. The following three beam and column configurations occurring in the structure are to be evaluated:

Set 1: Column W14×500, Beam W36×150
Set 2: Column W14×283, Beam W30×99
Set 3: Column W14×257, Beam W27×84

All columns are A572, Gr. 50 steel (expected F_y = 57.2 ksi; 394.4 MPa) and beams are A36 steel (expected F_y = 49.2 ksi; 339.2 MPa).

Estimate of maximum story drift demand:

$$\theta_{i,ST,\max} = \alpha_{MDOF} \times \alpha_{INEL} \times \alpha_{P\Delta} \times \alpha_{ST} \left(S_d / H \right)$$

$$= \alpha_{MDOF} \times \alpha_{INEL} \times \alpha_{P\Delta} \times \alpha_{ST} \left[\left(\frac{T}{2\pi} \right)^2 \left(\frac{S_a}{H} \right) \right]$$

(from Eq. 1)

$$\alpha_{MDOF} \approx 1.1 \times 1.4$$

$$\alpha_{INEL} \approx 0.75$$

$$\alpha_{P\Delta} \approx \frac{1}{(1-0.1)}$$

$$\alpha_{ST} \approx 2$$

The factor of 1.1 in α_{MDOF} is taken based on the height of the structure to account for some higher mode effects; α_{INEL} is taken as 0.75 as inelasticity is expected at both hazard levels   this assumption will be verified based on the estimate of story drift demand vis- -vis the estimate for story yield drift; $\alpha_{P\Delta}$ is based on a maximum story stability coefficient of 0.1; α_{ST} of 2 represents a maximum drift value over all stories, but is used here as a conservative value for each story.

The values for the various modification factors are based on Gupta and Krawinkler (2000a). Using Equation 1 and the modification factors values for the maximum story drift; the total drift demand is estimated to be 0.015 for the 475-year hazard level and 0.030 for the 2475-year hazard level.

Estimate of story yield drift demand:

The story yield drift (and the story plastic drift) is calculated using Equations 2 to 9. The results are shown in Table A.1, which also shows the contribution of the various elements to the story yield drift. The shear force in the column at connection yield is controlled by yielding of the beams for Set 1, while the panel zones yield prior to the beams in Set 2 and Set 3. The estimated values indicate that at the 475-year hazard level the maximum expected ductility demand is about 1.5 and at the 2475-year hazard level it is about 3.

Estimate of element deformation demands:

Equations 10 to 15 are used to determine the element plastic deformation demands. Strain hardening is taken as 3 percent. Since the estimated plastic deformation demands for the panel zones do not exceed three times the yield drift for the panel zones, Equations 16 and 17 are not used. For Set 1, Equation 15 returned a value of the beam plastic deformation that was greater than the story plastic deformation demand consequently; the panel zone plastic deformation demand was negative. For such cases, the complete solution is obtained through Equation 10, while assigning the element with negative deformation demand a null value. The final results are shown in Table A.2.

The results indicate that for Set 1 the deformation demand is localized in the beams at both hazard levels, while the demands are distributed between the beams and panel zones for Set 2 and Set 3. The ratio of deformation demands between the beams and panel zones changes with the hazard level, with the beams accounting for a larger portion of the plastic demand at the 2475-year hazard level. This is because after yielding of both the beams and panel zones, an equal percentage increase in beam and panel zone force demand results in higher beam plastic deformation on account of the lower post-yield stiffness of the beam relative to the second slope of the panel zone shear force shear distortion relationship.

Table A.1. Contribution of Different Elements to Story Yield Drift

	Beam	Column	Doubler Plate Thickness	δ_b/h	δ_c/h	δ_{pz}/h	$\theta_{y,st}$
Set 1	W36x150	W14x500	0.00	0.0061	0.0013	0.0020	0.0093
Set 2	W30x99	W14x283	0.00	0.0063	0.0014	0.0024	0.0101
Set 3	W27x84	W14x257	0.00	0.0069	0.0014	0.0024	0.0106

Table A.2. Element Plastic Deformation Demands at 475- and 2475-Year Hazard Levels

			475-Year Hazard Level			2475-Year Hazard Level		
	Beam	Column	$\theta_{p,st}$	$\theta_{p,b}$	$\theta_{p,pz}$	$\theta_{p,st}$	$\theta_{p,b}$	$\theta_{p,pz}$
Set 1	W36x150	W14x500	0.0057	0.0057	0.0000	0.0207	0.0207	0.0000
Set 2	W30x99	W14x283	0.0049	0.0007	0.0053	0.0199	0.0144	0.0070
Set 3	W27x84	W14x257	0.0044	0.0002	0.0051	0.0194	0.0139	0.0067