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PERFORMANCE BASED DESIGN USING FORCE REDUCTION FACTOR AND DISPLACEMENT AMPLIFICATION FACTORS FOR BFS

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ABSTRACT

In performance based design, the hazard levels and relevant acceptable damages are clearly specified. Structural and non-structural performances are controlled by limiting stiffness, strength and members ductility characteristics. Using displacement amplification factors (C_d) and force reduction factors (R) related to hazard levels, this paper present a method for determination of the stiffness and strength demands needed for BFs (Braced Frames) design. It means that two force reduction factors and two displacement amplification factors are introduced for moderate and major earthquake levels (Immediate Occupancy and Life Safety performances) for determination of stiffness and strength demands. These factors depend on ductility factor, force reduction factor due to ductility and overstrength factor. The procedure for determination of R and C_d factors and value of these factors for Io and LS performance level will be presented in this paper. The results indicate that force reduction factors and displacement amplification factors may be easily used in performance based design methodology.

Keywords: Displacement amplification factor; force reduction factor; overstrength factor; performance based design; reduction factor due to ductility

1. INTRODUCTION

In several countries, seismic design is in the process of change. Conventional methods of seismic design have the objectives to provide for life safety and damage control (The IBC and other design codes do not guarantee any damage control). In current design codes procedures, there are uncertainties concerning the seismic demand and seismic capacity of

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the structures. Performance based design is a design method in which the design criteria are expressed in terms of achieving stated performance objectives (redundant). In this method, the hazard levels and relevant acceptable damages are clearly specified. Structural and non-structural performances are controlled by limiting stiffness, strength and member ductility characteristics. In order to participating these characteristics (stiffness and strength) to structural design seismic performance factors need to be evaluated. Force reduction factors (R) and displacement amplification factors (C_d) can be obtained by using inelastic analysis on primary structural models [1].

Conventional concentric Braced Frame (CBF) and buckling restrained braced frame (BRBF) are among the most efficient concentric brace type of structural systems in steel construction for resisting lateral forces due to wind and earthquakes. In CBFs, the steel braces contribute to seismic energy dissipation by yielding in tension and buckling inelastically in compression whereas in BRBFs, the braces yield in both tension and compression. Different types of concentric braced frames exhibit different responses and consequently meet certain performance objectives differently. Performance based design permits design of new or upgrade of existing concentric brace frames.

Several researchers have investigated the performance and responses of structural frame systems. Considering force reduction factors and displacement amplification factors, Mahmoudi [2] present a design methodology for calculation of primary stiffness and strength demands for reinforced concrete moment resisting frames in order to implement performance based design criteria. Force reduction factors proposed by Mahmoudi for IO, LS and CP performance level are 2.28, 4.43, 5.30 and displacement amplification factors are 2.29, 4.73, 5.83, respectively. Evaluating overstrength, ductility and response modification factors of the concentrically braced steel frames, Mahmoudi and Zaree [3,4] showed that structural characteristics have great effect on these factors. Considering the intended performance objectives in terms of yield mechanisms and target drift levels, Sahoo and Chao [5] presented a performance based plastic design methodology for the design of buckling restrained braced frames.

In this paper a method will be proposed for determination of the stiffness and strength demands needed for steel resisting CBFs and BRBFs design. Using inelastic analysis for this purpose, force reduction factors (R) and displacement amplification factors (C_d) related to hazard levels were evaluated. It means that two R and two C_d are determined and introduced for moderate and major earthquake levels (or two structural performances controls; Immediately Occupancy (IO) and Life Safety (LS)). Considering CBFs and BRBFs, the main objective of this study is to present the procedure for evaluation of force reduction factors and displacement amplification factors in two structural performances levels (IO and LS) suggested by FEMA-356 [6]. This methodology provides factors for assessing the performance capability of the CBFs and BRBFs.

2. PERFORMANCE BASED DESIGN

Recently, performance based design for structures under strong ground motion have been gaining great attention. The basic concept of performance based design is to provide

engineers with the capability to design buildings that have a predictable and reliable performance in earthquake. The performance is a direct relationship to the damage sustained by the building in a design event. In order to determine the performance of the building in an earthquake, FEMA 356 [6] separates building components into two categories, structural and nonstructural. The structural performance levels and the nonstructural performance levels can be combined in any number of ways to reach a desired target building performance level or range. The target building performance levels are Operational Performance (OP), Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). Figure 1 illustrated target performance levels. Each performance objective is a statement of the acceptable risk of incurring specific levels of damage, and the consequential losses that occur as a result of this damage, at a specified level of seismic hazard.

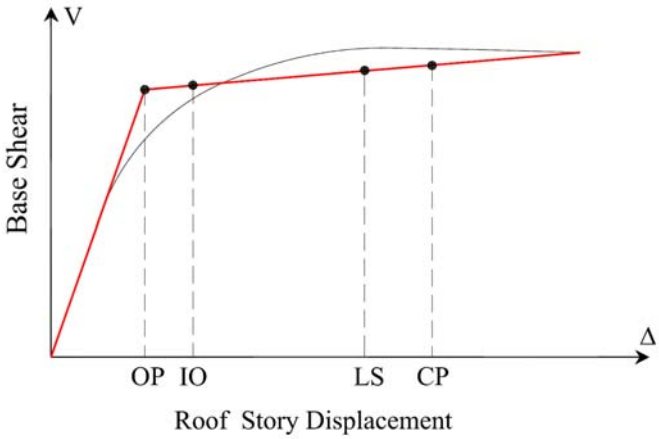

Figure 1. Illustration of target performance levels [6]

For OP, building are expected to sustain minimal or no damage to their structural and nonstructural components. For IO, buildings expected to sustain minimal or no damage to their structural elements and only minor damage to their nonstructural components. The risk to life safety at this target building performance level is very low. For LS performance, Buildings may experience extensive damage to structural and nonstructural components and the risk to life safety is very low too. For CP, buildings may pose a significant hazard to life safety resulting from failure of nonstructural components. So many buildings will be complete economic losses [6].

Life safety is the base performance level that most of code's considered for response parameters in earthquake ground motion. Failure due to human errors, structural deflection and nonstructural elements damages cause great losses. So, consideration one performance level (LS) to predict performance response is not enough. Many building owners may wish to achieve IO performance when the building is subjected to moderate earthquake ground motion and desire to meet LS building performance level for severe ground shaking. In this paper IO and LS target performance level were considered in order to finding seismic performance factors.

3. SEISMIC PERFORMANCE FACTORS

Figure 2 explained seismic performance factors given by the base shear versus roof displacement relation of a structure, which can be developed by a nonlinear static analysis.

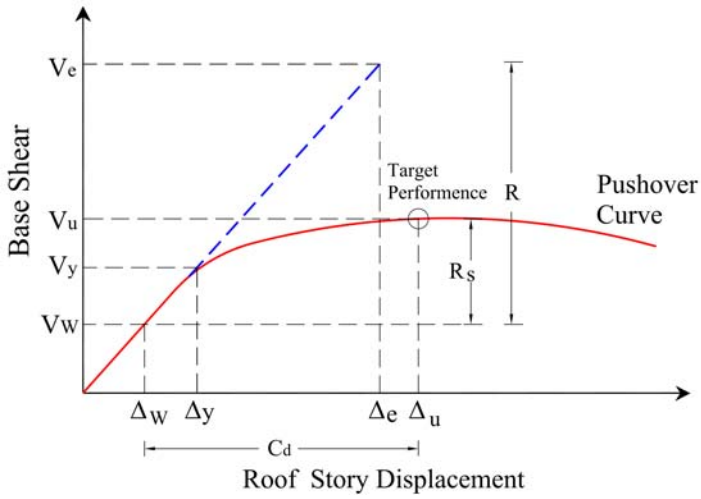

Figure 2. General structural response [7]

In Figure 2, V_w and Δ_w are design base shear and displacement, V_y and Δ_y are yield base shear and displacement, V_u and Δ_u are base shear and displacement relevance to the first target performance level in structure member.

Force reduction factors and displacement amplification factors are determined as follows:

$$R = R_\mu . R_S \tag{1}$$

$$C_d = \mu . R_S \tag{2}$$

Where, R_μ is a reduction factor due to ductility, R_S is the overstrength factor and μ is structural ductility factor written as:

$$\mu = \frac{\Delta_u}{\Delta_y} \tag{3}$$

Reduction factor due to ductility is defined for equivalent single-degree-of-freedom (SDOF) system. Several proposals have been made for R_μ by Newmark and Hall [8], Riddell [9], Krawinkler [10], Miranda [11] and Fajfar [12]. In simple version of the N2 method the R_μ proposed by Fajfar [13] as follow:

$$\begin{aligned} R_\mu &= (\mu - 1)\frac{T}{T_C} + 1 \quad (T < T_C) \\ R_\mu &= \mu \quad (T \geq T_C) \end{aligned} \tag{4}$$

Where, T is the fundamental period and T_C is the characteristic period of the ground motion.

Overstrength is the lateral strength of the structures from the strength associated to the design level to the strength associated to the formation of a target performance level. The value of overstrength factor will be determined as:

$$R_S = 1.155 \frac{V_u}{V_W} \tag{5}$$

In steel structure, the value 1.155 is consider for difference between actual and nominal static yield strengths and increase in yield stress as a result of strain rate effect during an earthquake [13, 14].

4. STRUCTURAL MODELS

In order to determine of force reduction factors and displacement amplification factors, 30 conventional concentric braced frames (CBFs) and 20 buckling restrained braced frames (BRBFs) having three, five, seven, ten and twelve stories and bays of 5m long were selected. For CBFs and BRBFs bracing type (X, chevron V and chevron-inverted V) were located in single and double bays. The buildings are assumed to be located on a soil type II and in a seismically active area, zone 1 (with seismic zone factor A=0.35) of the Iranian Earthquake Resistance Design Code (Standard No. 2800) [15]. Force reduction factors R=6 and 8 were considered for primary CBFs, and BRBFs design [15,16]. Figure 3 shows the elevation view of some studied frames while plan views of the structures are shown in Figure 4.

These frames were loaded, analyzed and designed according to Iranian Earthquake Resistance Design Code (Standard No. 2800) [15], Iranian National Building Code, part 10, steel structure design [17] and seismic provision of AISC [18].

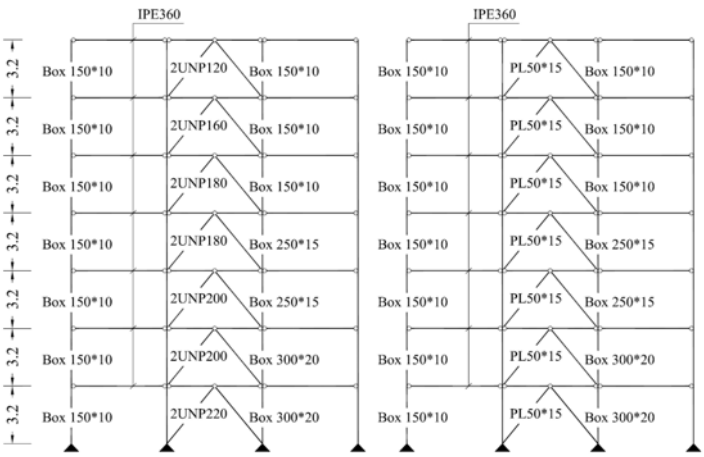

Figure 3. Elevation view of the studied structures

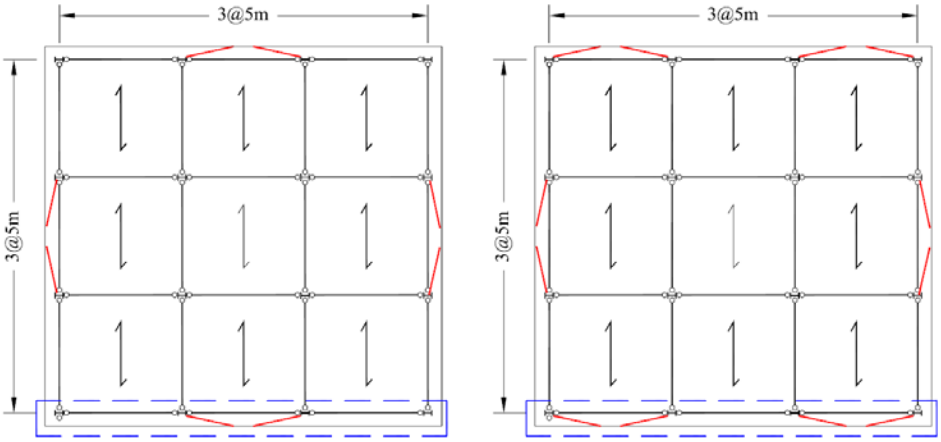

Figure 4. Plan layout of model structures

To evaluate the seismic performance factors, inelastic static analyses (pushover analyses) were carried out for selected steel frame systems. The analysis was conducted using modeling parameters and acceptance criteria for nonlinear procedures of structural steel members suggested by FEMA-356 [7]. The model present in FEMA-356 for brace in tension is applied for both tension and compression behavior of buckling restrained brace members.

5. RESULTS

Using pushover analysis, a characteristic nonlinear force- displacement relation of frame systems can be determined. Figures 5 and 6 show Roof displacement-base shear curves of five and ten story CBFs and BRBFs with single and double invert-V bracing bays. The values of overstrength factors, ductility factors, reduction factors due to ductility, force reduction factors and displacement amplification factors for all frames in two performance levels (IO and LS) are presented Tables 1and 2.

Table 1: Seismic performance factors for conventional CBFs

Frame type		No. story	μ		R_S		R_μ		R		C_d	
			IO	LS	IO	LS	IO	LS	IO	LS	IO	LS
Single bay conventional CBFs	Chevron invert-V	3	1.21	1.45	4.19	4.24	1.14	1.31	4.78	5.55	5.05	6.15
		5	1.36	1.44	3.72	3.75	1.36	1.44	5.05	5.40	5.05	5.40
		7	1.35	1.39	3.69	3.72	1.35	1.39	4.98	5.17	4.98	5.17
		10	1.27	1.30	3.49	3.51	1.27	1.30	4.44	4.56	4.44	4.56
		12	1.27	1.29	3.47	3.50	1.27	1.29	4.41	4.51	4.41	4.51
	Chevron V	3	1.40	1.47	3.55	3.82	1.27	1.32	4.52	5.04	4.97	5.65
		5	1.34	1.38	2.95	2.98	1.34	1.38	3.95	4.11	3.95	4.11
		7	1.38	1.42	2.85	2.88	1.38	1.42	3.93	4.08	3.93	4.08
		10	1.29	1.35	2.76	2.80	1.29	1.35	3.56	3.78	3.56	3.78
		12	1.26	1.32	2.75	2.78	1.26	1.32	3.46	3.66	3.46	3.66
	X brace	3	1.67	1.72	3.59	3.61	1.46	1.49	5.23	5.38	6.00	6.06
		5	1.48	1.51	3.37	3.38	1.48	1.51	4.98	5.10	4.98	5.10

Double bays conventional CBFs	Chevron invert-V	7	1.49	1.52	3.04	3.05	1.49	1.52	4.53	4.64	4.53	4.64
		10	1.42	1.48	2.91	2.92	1.42	1.48	4.13	4.32	4.13	4.32
		12	1.39	1.42	2.85	2.86	1.39	1.42	3.96	4.06	3.96	4.06
	Chevron V	3	1.45	1.52	6.02	6.09	1.31	1.35	7.87	8.22	8.73	9.31
		5	1.20	1.26	5.03	5.08	1.20	1.26	6.04	6.40	6.04	6.40
		7	1.20	1.25	4.71	4.74	1.20	1.25	5.65	5.92	5.65	5.92
		10	1.16	1.19	4.66	4.70	1.16	1.19	5.41	5.59	5.41	5.59
		12	1.16	1.18	4.25	4.29	1.16	1.18	4.93	5.06	4.93	5.06
	X brace	3	1.33	1.38	5.14	5.22	1.22	1.26	6.29	6.58	6.83	7.25
		5	1.28	1.34	4.01	4.05	1.28	1.34	5.13	5.43	5.13	5.43
		7	1.24	1.28	3.63	3.67	1.24	1.28	4.50	4.69	4.50	4.69
		10	1.24	1.26	3.42	3.41	1.24	1.26	4.24	4.29	4.24	4.29
		12	1.23	1.26	3.25	3.27	1.23	1.26	4.00	4.05	4.00	4.05
		3	1.50	1.51	5.86	5.86	1.34	1.34	7.85	7.85	8.78	8.79
		5	1.41	1.44	4.44	4.46	1.41	1.44	6.25	6.28	6.25	6.28
		7	1.43	1.45	4.13	4.16	1.43	1.45	5.91	6.03	5.91	6.03
		10	1.36	1.37	3.95	3.96	1.36	1.37	5.37	5.42	5.37	5.42
		12	1.35	1.37	3.66	3.67	1.35	1.37	4.94	5.03	4.94	5.03

Table 2: Seismic performance factors for BRBFs

Frame type		No. story	μ		R_S		R_μ		R		C_d	
			IO	LS	IO	LS	IO	LS	IO	LS	IO	LS
Single bay BRBFs	Chevron invert-V	3	2.21	9.45	2.06	2.41	1.83	6.76	3.76	16.30	4.85	22.82
		5	1.68	8.94	1.55	1.78	1.68	8.94	2.60	15.90	2.60	15.90
		7	1.87	7.54	1.52	1.74	1.87	7.54	2.84	3.12	2.84	13.12
		10	1.59	5.91	1.37	1.57	1.59	5.91	2.18	9.27	2.18	9.27
		12	1.41	5.02	1.23	1.40	1.41	5.02	1.73	7.02	1.73	7.02
	Chevron V	3	1.78	8.77	2.11	2.53	1.53	6.30	3.23	15.93	3.76	22.18
		5	1.69	8.07	1.59	1.85	1.69	8.07	2.69	14.96	2.69	14.96
		7	1.60	7.25	1.53	1.84	1.60	7.25	2.45	13.34	2.45	13.34
		10	1.49	5.49	1.46	1.70	1.49	5.49	2.17	9.33	2.17	9.33
		12	1.38	4.75	1.35	1.58	1.38	4.75	1.86	7.50	1.86	7.50
Double bays BRBFs	Chevron invert-V	3	1.16	9.33	2.86	3.41	1.11	6.68	3.17	22.85	3.32	31.80
		5	1.52	7.31	2.24	2.60	1.52	7.31	3.40	19.00	3.40	19.00
		7	1.27	6.72	2.06	2.36	1.27	6.72	2.61	5.89	2.61	5.89
		10	1.39	6.25	1.74	2.00	1.39	6.25	2.42	2.51	2.42	2.51
		12	1.30	5.25	1.55	1.78	1.30	5.25	2.02	9.34	2.02	9.34
	Chevron V	3	1.63	8.89	2.82	3.39	1.43	6.38	4.03	21.62	4.60	30.13
		5	1.43	7.09	2.09	2.43	1.43	7.09	2.98	17.23	2.98	17.23
		7	1.43	6.91	1.93	2.19	1.43	6.91	2.76	15.13	2.76	15.13
		10	1.35	6.24	1.53	1.76	1.35	6.24	2.07	10.98	2.07	10.98
		12	1.27	5.11	1.30	1.48	1.27	5.11	1.65	7.56	1.65	7.56

In Figure 5 the initial slop of the curves is different so for CBFs with changes on number of bracing bays and frame height, initial stiffness and overstrength have large difference. Results indicate that CBFs have high stiffness. This stiffness is because of design codes seismic provision for brace member design that causes higher overstrength factors in comparison with BRBFs. On the other hand, low ductility of CBFs is because of brace member weakness on energy dissipation capacity proposed by FEMA356 [6].

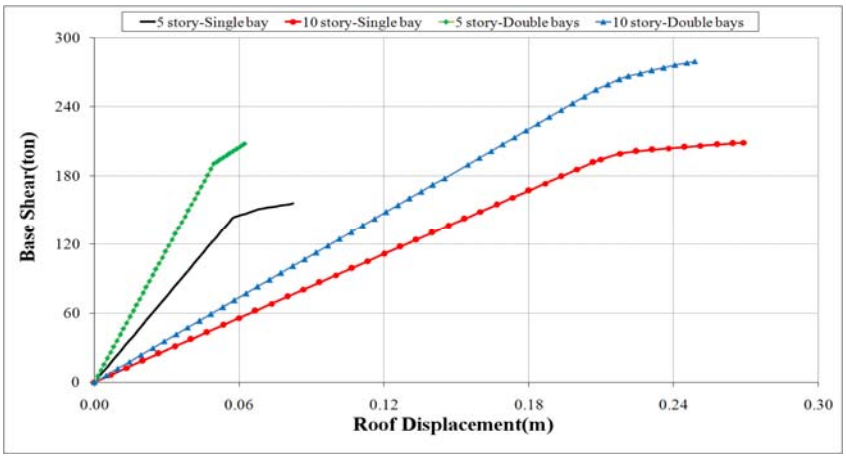

Figure 5. Roof displacement-base shear curve for single and double bays invert-V CBFs

Ductility factors as well as reduction factors due to ductility for BRBFs have high values. Nonlinear behavior model for BRBFs members gather great energy dissipation capacity which results high ductility for these frames, Figure 6. Beside, approximately the same initial slop of these frame curves causes equal values of overstrength for each type of BRBFs with different height.

In CBFs and BRBFs, performance factors for chevron invert-V type brace frames have higher value in comparison with chevron V and X brace frames. As can be seen performance factors for IO and LS in CBFs are close to each other. The beam-column connections were assumed to be pinned in CBFs and BRBFs so that brace member nonlinear model is the main parameter for determine these frames behavior. According to FEMA, conventional braces have weak energy dissipation capacity caused the same IO and LS performance factors for CBFs.

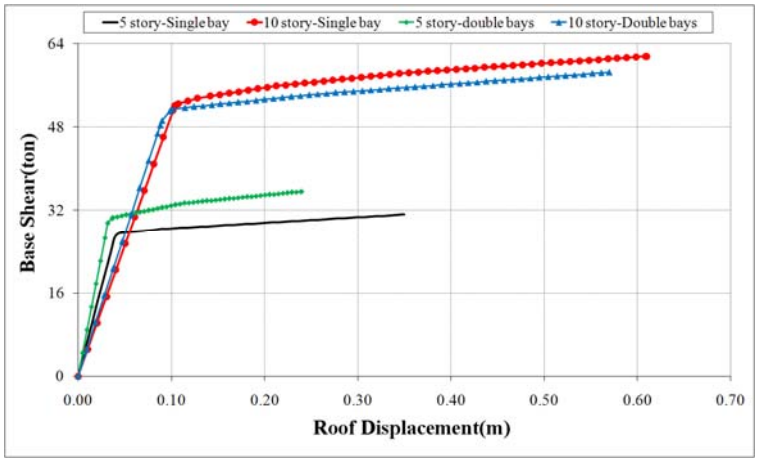

Figure 6. Roof displacement-base shear curve for single and double bays invert-V BRBFs

6. CONCLUSION AND SUGGESTIONS

The paper presents a design methodology for calculation of stiffness and strength demands for steel moment resisting frames, conventional concentric braced frames and buckling restrained braced frames in order to implement performance based design criteria. In this methodology, it is used two force reduction factors (R) and two displacement amplification factors (C_d) for two performance levels (Immediately Occupancy and Life Safety).

Using R factors, the structural elastic strength demands will be determined and using C_d factors, the structural stiffness demands will be obtained. With this process the dimensions of members will be designed. It was observed that force reduction factors and displacement amplification factors of CBFs and BRBFs decrease with an increase in the height of buildings. Also, steel frame characteristics (such as number of bracing bays) have an effect on performance factors.

Considering lateral load resistant systems, performance factors for steel frames are different. Table 3 presented the force reduction factors and displacement amplification factors for concentric braced steel frame systems. IO and LS performance factors for CBFs are approximately equal but for BRBFs there is specified difference on these performance level.

Table 3: Seismic performance factors for concentric braced steel frame systems

Performance factor	**Single bay CBFs**		**Double bays CBFs**		**Single bay BRBFs**		**Double bays BRBFs**	
	IO	**LS**	**IO**	**LS**	**IO**	**LS**	**IO**	**LS**
R	4.40	4.62	5.63	5.79	2.55	11.30	2.71	13.21
C_d	4.49	4.75	5.78	5.97	2.71	13.55	2.78	14.95

Based on the results the strength demands (evaluated by structural analysis subjected to reduced earthquake loads), strength capacities and maximum lateral displacement (introduced by seismic codes) for concentric braced steel frame systems must be checked.

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