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Estimating displacement demand in reinforced concrete frames using some failure criteria

Benyamin Monavari and Ali Massumi*

Abstract

Under seismic loads on structures, the maximum drift without total collapse is called target displacement. Most of low- and medium-rise building structures are seismically designed using equivalent static method. In equivalent static method, design forces are obtained from elastic spectra which are reduced using response modification factor. This coefficient represents the structures' inelastic performance and indicates strength and hidden ductility of structures in inelastic phase. The ultimate deformation of the structure to its deformation in yielding is called ductility coefficient which expresses the inelastic deformation capacity of structures. The larger this coefficient, the higher the level of energy absorption and the more the formation of plastic joints, so accurate determination of yielding points and ultimate displacements are very important. In this paper some failure criteria are used to estimate seismic demands for buildings. To investigate these criteria, pushover analysis is done on reinforced concrete frame buildings. Using a combination of these criteria will lead to displacements that are closed to the target displacement presented in FEMA-356.

Keywords: Target displacement, Failure criteria, Reinforced concrete frame, Pushover, FEMA-356

Introduction

Nonlinear static analysis is a simple technique which can be used to estimate dynamic demands of structures under seismic excitations. Some investigations are made by Krawinkler and Seneviratna (1997), Gupta and Krawinkler (2000), Rofooei et al. (2006), Shakeri et al. (2010), and Jiang et al. (2010) to estimate demands for buildings by using the pushover analysis. Also, many other methods and criteria are used to estimate target displacement of structures. Recently, some investigations have done this to obtain the target displacements from various procedures (Gupta and Krawinkler (2000), Shakeri et al. (2010), Jiang et al. (2010). One of the widely used procedures to estimate the target displacement in the nonlinear static procedure is the coefficient method defined in the FEMA-356 document (The American Society of Civil Engineers for the Federal Emergency Management Agency 2000), but in this paper, nonlinear static analysis and five local and overall yields and failure criteria are used to estimate seismic demands of buildings. Failure is the losing of the structure's performance during an earthquake or its subsequent effects. Due to the consequent excitations of an earthquake or lateral imposed loads on a structure, the stiffness of some elements of the structure decreases and the structure starts to lose its performance. This failure may also happen in small parts of the structure or even the whole part of it. The damage of the structures under lateral loads is a major problem in civil engineering. Some damage indices are suggested to delimit these damages (such as in Lybas and Sozen (1977), Shah (1984), Park et al. (1987), Oh (1991), and Sadeghi (1998). Some investigations are done by using these damage indices such as in Park et al. (1988), Ladjinovic and Folic (2004), Sawada et al. (2004), De Guzman and Ishiy Ama (2004), Sadeghi and Nouban (2010), Yuchuan et al. (2011), and Ghosh et al. (2011).

The following parts of this study structures are analyzed using nonlinear static analyses. Some collapse criteria are investigated based on the results of these analyses, and in the end, the conclusions are compared with FEMA-356.

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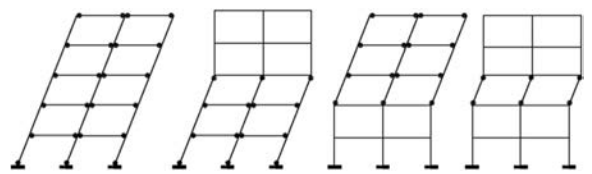

Figure 1 **Four overall instability cases.**

Methods

In this study thirteen reinforced concrete (RC) frame buildings with 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 16, and 20 stories, having three and four bays, were designed using seismic force levels obtained from the Iranian Seismic Code (2005) (Building and Housing Research Center 2005) and proportioned using the ACI318-99 Building Code (American Concrete Institute Committee 318 (1999) and then were modeled by a program for inelastic damage analysis of reinforced concrete (IDARC). Push-over analysis with increasing triangular loading is used.

The investigated criteria are expressed as follows:

(a) Exceeding member curvature from the final member curvature (φ),
(b) Exceeding inter-story drift from a maximum amount (ID),
(c) Structural instability due to hinges formation and mechanism (SI),
(d) Exceeding the Park-Ang damage index from unit (DI), and
(e) Exceeding stability index from a defined limit (θ).

Definitions of criteria used in this study

Exceeding member curvature from the final member curvature (φ)

As mentioned in Valles et al. (1996), the ultimate deformation capacity of a section is considered as its ultimate curvature. Curvature analysis is done on the cross-section by using a fiber model. The incremental curvature that is applied to the section is continued until either the specified ultimate compressive strain in the concrete or the specified ultimate strength of one of the rebar is reached.

Exceeding inter-story drift from a maximum amount (ID)

This criterion indicates that if the inter-story drift of structures for every floor exceeds from 3% (it is the maximum amount considered in standard number 2800 of Iranian Seismic Code (2005)), the story will collapse.

Structural instability due to hinges formation and mechanism (SI)

This criterion is used when instability happens in whole or a part of structure due to hinges formation and mechanism. There are four overall instability cases, due to structures geometry as shown in Figure 1.

Exceeding the Park-Ang damage index from unit (DI)

Damage indices are investigated by many researchers such as Park et al. (1988), Ladjinovic and Folic (2004), De Guzman and Ishiy Ama (2004), Sadeghi and Nouban (2010), and Ghosh et al. (2011). The Park-Ang damage index was developed based on experimental studies and observing damages in actual buildings. As defined in Park and Ang (1985),

$$\mathrm{DI}_{\mathrm{P\ 38A}} = \frac{\delta_m}{\delta_u} + \frac{\beta \int dE_h}{\delta_u P_y} \tag{1}$$

where δ_m is the maximum experienced deformation; δ_u is the ultimate deformation of the element; P_y is the yield strength of the element; dE_h is the incremental dissipated hysteretic energy; β is the model constant parameter; and DI < 0.4 means repairable damage; 0.4 ≤ DI ≤ 1 means damage beyond repair; DI \rm\scale120%≥ 1 means the loss of a building or story.

To verify these parameters, journals of Park et al. (1988) and De Guzman and Ishiy Ama (2004) are used.

Exceeding stability index from a defined limit (θ)

Exceeding stability index from θ_{max}. According to Iranian Seismic Code, the stability index defined as

$$\theta_i = \frac{\Delta V_i}{V_i} = \text{Interstory drift.} \frac{\text{Verticalloads}}{\text{Story shear}} \tag{2}$$

where ΔV_i is the added shear in ith floor created by $P - \Delta$ effects

$$\Delta V_i = \frac{P_i \Delta_i}{h_i} \tag{3}$$

and P_i is the total dead and live loads for the ith floor and its higher floors; Δ_i is the inter-story drift of the ith floor; h_i is the height of the ith floor and

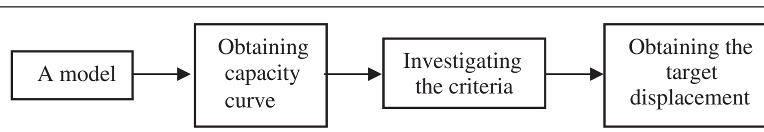

Figure 2 **Procedure to obtain the target displacement.**

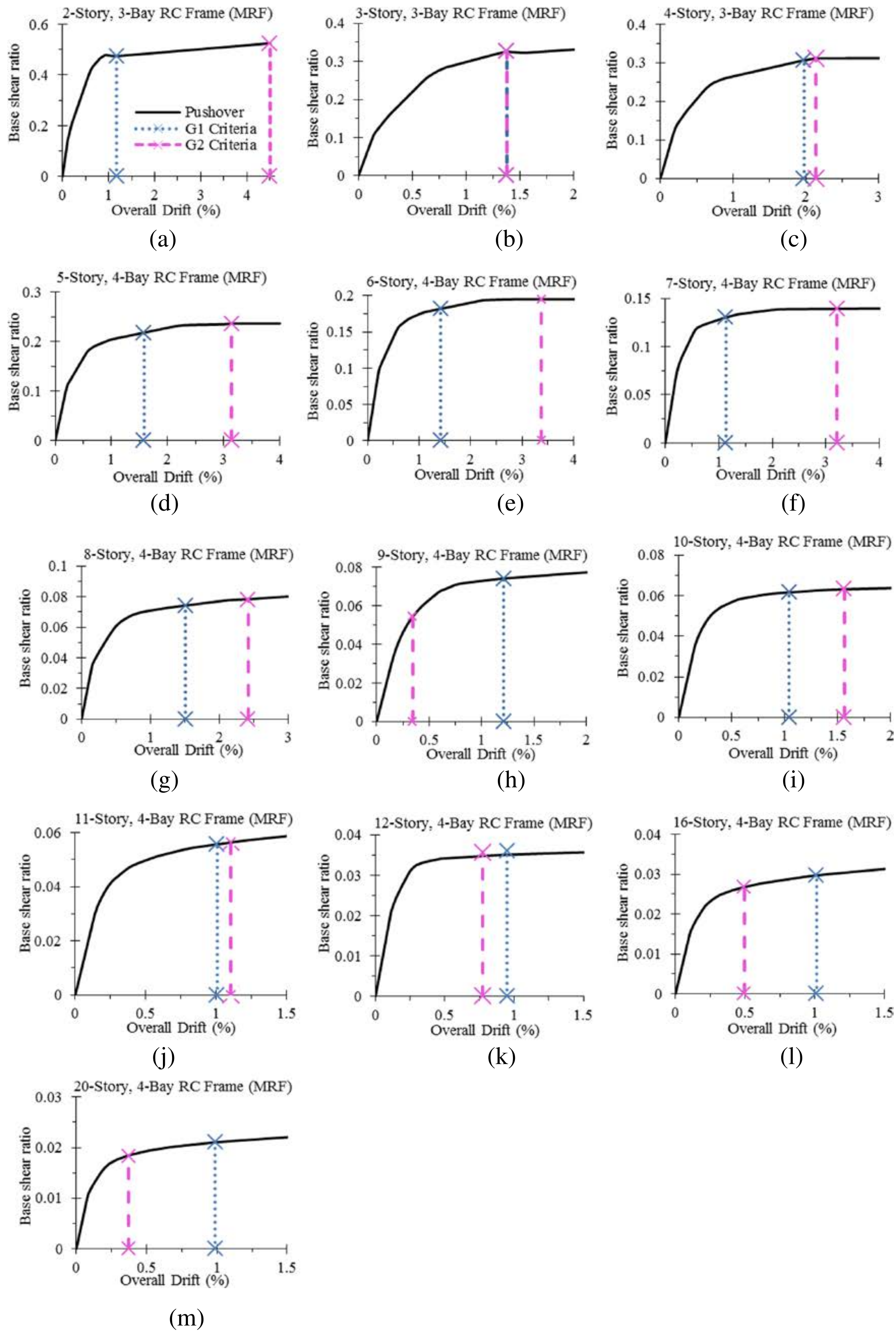

Figure 3 (See legend on next page.)

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Figure 3 Investigation of collapse criteria. (**a**) 2-story, 3-bay frame; (**b**) 3-story, 3-bay frame; (**c**) 4-story, 3-bay frame; (**d**) 5-story, 4-bay frame; (**e**) 6-story, 4-bay frame; (**f**) 7-story, 4-bay frame; (**g**) 8-story, 4-bay frame; (**h**) 9-story, 4-bay frame; (**i**) 10-story, 4-bay frame; (**j**) 11-story, 4-bay frame; (**k**) 12-story, 4-bay frame; (**l**) 16-story, 4-bay frame; and (**m**) 20-story, 4-bay frame.

$$\theta_{\max} = \frac{1.25}{R} \leq 0.25. \tag{4}$$

Defined procedure to calculate target displacement

Figure 2 illustrates the procedure for obtaining the target displacement is defined in this study. Capacity curves of the structures are calculated and plotted by IDARC. Then three criteria including DI, SI, and ϕ are considered for failure points of the structure and then, criteria of ID and θ are studied (these two criteria usually notify the collapse in displacements less than the other criteria). In this study we have two groups of criteria which are called G1 and G2. G1 contains SI, DI, ϕ, and ID criteria, and G2 contains SI, DI, ϕ, and θ criteria. The results of each group are seen in Figure 3.

The results are brought in Figure 4 after investigating the two groups of criteria for each structure. As shown in this figure, the criteria of the second group (G2), due to θ criterion, have a lot of dispersion and do not give good results, therefore, need more investigations. But criteria of the first group (G1) provide acceptable results. The maximum amount of drifts based on G1 criteria is for four-floor structure and is about 2%, but the minimum amount is for ten-floor structure and this one is about 1%. Because of the logical amounts of ultimate drifts, the G1 criteria are chosen for obtaining the target displacements.

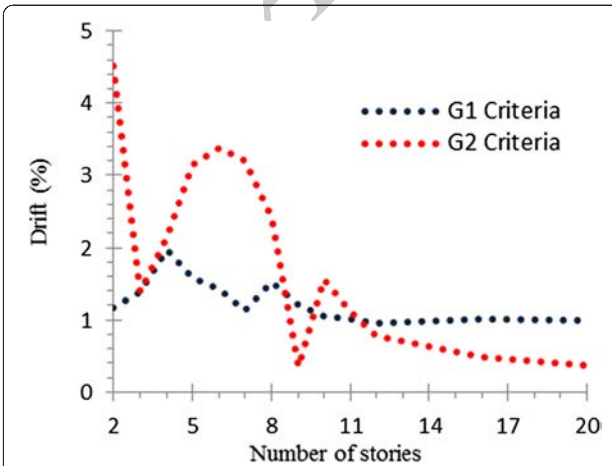

Figure 4 Results of the collapse criteria investigations.

The G1 criteria are investigated for the structures. As shown in Figure 5, total collapses occurred at the level of the upper half of structures' height, 85% of which occurred at the level of 50% to 80% of the structures' height. For structures with fewer floors, total collapses occurred approximately at the levels close to the roof. By increasing the number of floors, the total collapses occurred at lower levels of the roof. Finally for structures with more than eleven floors, total collapses occurred at the middle height of the structures.

Procedure to compute target displacement by FEMA-356

The FEMA-356 recommends the following equation for computing the target displacement:

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^{\,2}}{4\pi^2} g. \tag{5}$$

See FEMA-356 for details. In Figure 6 the target displacements for each structure computed by FEMA-356 are seen.

Results and discussion

In this study five criteria were used, four of which were considered as failure displacement. In a seismic excitation these structures certainly do not collapse before reaching these failure displacements. Considering failure displacements in this study, an approximate equation with the best curve close to the mentioned displacement is obtained. This equation is acceptable for the structures of various floors. This curve can be seen in Figure 7.

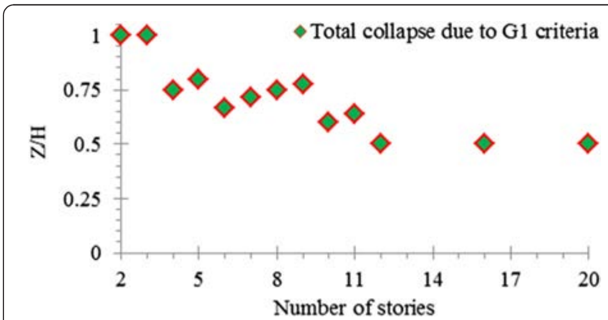

Figure 5 Investigation of the total collapse due to G1 criteria.

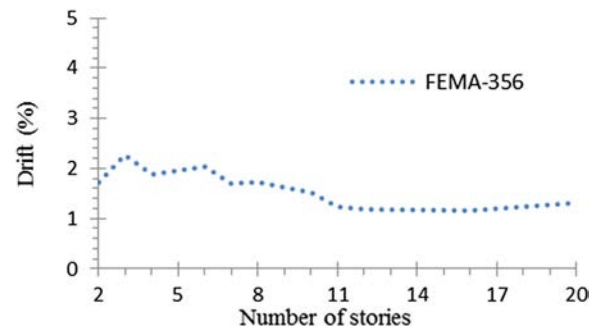

Figure 6 **The target displacements attained by FEMA-356.**

The approximate equation can be expressed as

$$D_t = a - b\exp\left(cN^d\right) \quad \text{for } N = 2, \ldots, 10 \qquad (6a)$$

$$D_t = 1 \quad \text{for } N \geq 11 \qquad (6b)$$

where N = number of stories, a = 1.5, b = 3.28, c = −32.41, and d = −1.16.

The given equation is acceptable for RC frame buildings studied in this paper with two to twenty floors, but for using this equation for more floors, more study is needed.

Both the results of this study and target displacements obtained from FEMA-356 are put in Figure 8.

Conclusions

In this paper obtaining the target displacement two groups of criteria were considered and then pushover analyses were done, and, in the end, the target displacements for thirteen frame buildings were obtained.

As shown for the chosen criteria, total collapses occurred at the level of the upper half of structures' height, 85% of which occurred at the level of 50% to 80%. These results show that the medium heights of the structures have a greater impact on the ultimate deformation of the structures.

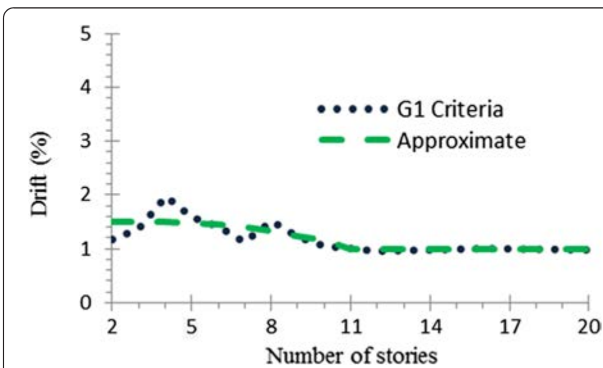

Figure 7 **The approximate of the attained target displacement by the new procedure.**

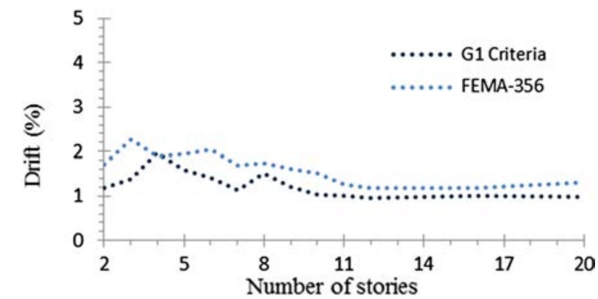

Figure 8 **The results of this study's procedure and FEMA-356.**

Totally, our investigations show that the obtained target displacements due to the procedure introduced in this study are about 1% to 2%, but for structures with more than ten floors, the chosen criteria lead to drifts about 1%. These results are approximately close to the obtained target displacements from FEMA-356; however, they are a little lower.

It is important to notice that these results are obtained under versus triangular loads. For more investigation it is proposed to repeat the study using seismic loads and modal pushover analysis.

Abbreviations

φ: exceeding member curvature from the final member curvature; θ: exceeding stability index from a defined limit; DI: exceeding the Park-Ang damage index from unit; ID: exceeding inter-story drift from a maximum amount; G1: the first group of collapse criteria that contains SI, DI, φ, and ID criteria; G2: the second group of collapse criteria that contains SI, DI, φ, and criteria; RC: reinforced concrete; SI: structural instability due to hinges formation and mechanism.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

The main idea of this paper was suggested, modified, and developed by AM. The modeling procedure and analytical solution were done by BM. Both authors read and approved the final manuscript.

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