INFLUENCE OF DIAPHRAGM FLEXIBILITY ON RESPONSE MODIFICATION FACTOR

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Abstract

Response modification factors are used in building seismic design to reduce design forces safely to economic levels based on the structures ability to deform and dissipate energy. The relationship between the response modification factor (R), structural ductility (μ) and structural period (T), known as the R-μ-T relationship, has been investigated by many researchers. In this past research, the R-μ-T relationship was studied using single-degree-of-freedom models representing rigid diaphragm structures. However, certain classes of buildings have flexible floor or roof diaphragms. The influence of diaphragm flexibility on the R-μ-T relationship has not been studied extensively. In this paper, diaphragm flexibility is considered in generating the R-μ-T relationship. A two-degree-of-freedom model was created by splitting the mass tributary to the lateral force resisting system and the mass tributary to the diaphragm. An elastic spring is used to connect the lateral force resisting system and the diaphragm, which representing the diaphragm flexibility. The R-μ-T relationships were then developed using nonlinear time history analyses for different diaphragm stiffness. Thirty ground motions recorded from historical far-field earthquakes on soil class D were used in the analysis. It has been found that the diaphragm flexibility tends to increase the structural ductility demand at a given R for short period buildings. For intermediate to long period buildings, the influence of diaphragm flexibility varies. The structural ductility demand can either increase or first increase and then decrease as the diaphragm flexibility increases, depending on the magnitude of R.

Keywords: ductility, response modification factor, far-field earthquakes, diaphragm flexibility, nonlinear time history analyses

1. Introduction

Response modification factor is used in building seismic design to reduce design forces safely to economic levels based on the structures ability to deform and dissipate energy. The response modification factor (R) is different for different seismic force resisting systems (SFRS) [1]. R is larger if the SFRS is more ductile and has larger energy dissipation capacities. However, R is considered depend not only on the SFRS, but also on other factors, like structural period, structural ductility, structural post-yield stiffness (or strain hardening ratio), damping, site soil condition. Plenty of research [2-10] has been done to investigate the influence to R from different factors and proposed different simplified equations to predict R. In proposed equations, R mostly depends on structural ductility (μ) and structural period (T), which is also known as the R-μ-T relationship. However, the factors in the equation expression may change when the structural damping ratio (ξ) and structural strain hardening ratio (γ) change. Previous research [2-10] used a single-degree-of-freedom system (SDOF) to investigate the R-μ-T relationship, with the assumption that the diaphragm is rigid. However, the rigid diaphragm assumption is not suitable to some structures (like parking garages). The diaphragm flexibility may make the structure behave differently from a rigid diaphragm structure [11, 12]. Therefore, it is worth to investigate how the diaphragm flexibility may influence R in comparison to that from rigid diaphragm buildings.

2. Previous research summary

As mentioned previously, SDOF is used for creating the R-μ-T relationship in previous research [2-10]. The SDOF period varies in a range (like 0s – 4s) and is subjected to nonlinear time history analyses using different earthquakes. The maximum SDOF response from each time history analysis is used to construct response spectrum for each earthquake. If the proposed R-μ-T relationship is from regression analysis, the relationship is constructed based on the average response spectrum of different earthquake response spectra. Or the study did some modification to the factors used to construct a piece-wise spectrum based on the response spectrum proposed by Newmark and Hall [13].

Lai and Biggs [3] investigated the influence from strong ground motion duration, ductility ratio, damping ratio to the inelastic acceleration and displacement response spectra. Four sets of artificial motions with strong motion durations of 10s, 20s, 30s and 40s were used for the study. Each set contains five different motions with a maximum ground acceleration of 1.0g. These motions match the Newmark-Hall elastic design response spectrum [13, 14]. Elasto-plastic system is used for the inelastic behavior of the SDOF model under investigation. The authors comment that at a given ductility ratio, the strong motion duration may not have significant influence to the SDOF inelastic responses.

Elghadamsi and Mohraz [4] showed that different soil structure and structural damping produce different response modification factors.

Nassar and Krawinkler [7] investigated the influence to R from different target ductility ratios, different strain hardening ratios, epicentral distances, two hysteresis models (bilinear and modified Clough stiffness degrading model), different structural periods. The damping ratio is 5%. 48 records are used in this analyses. The research shows that R is not sensitive to the epicentral distance. The effect of strain hardening ratio on the inelastic strength demands of bilinear SDOF is noticeable but not significant. The research also shows that if strain hardening ratio is 0, the stiffness degrading model allows a larger R than the bilinear model. This difference diminishes when the model incorporates strain hardening. The research provides the R-μ-T relationship through regression analysis. The R-μ-T relationship is based on the analysis results from the bilinear model and considers the effect of strain hardening ratios.

Miranda [8] classified 124 ground motion into three groups: ground motions recorded on rock (38 records), alluvium (62 records) and very soft soil deposits characterized by low shear wave velocities (24 records). The SDOF system used in the study has a 3% of strain hardening ratio and 5% of damping ratio. The research shows that the R-μ-T relationship using the earthquakes recorded on rock and alluvium are different from each other. However, this difference is not as significant as the difference between the R-μ-T relationship for soft soil sites and the R-μ-T relationship for either rock or alluvium sites. The research shows that the influence from earthquake magnitude on mean R-μ-T relationship is negligible when the earthquakes were recorded on rock sites. The research also shows that the influence from epicentral distance on the R-μ-T relationship is negligible, which is the same as the conclusion from [7].

Vidic et al. [9] commented that it is more accurate to derive the R-μ-T relationship through statistical studies of the spectra obtained by the nonlinear dynamic analysis of structures subjected to ground motions. Five group of earthquake records were used for the analyses and all the records were normalized to v_g = 50 cm/s. The authors also commented that in the case of obtaining non-dimensional quantities, like R, no normalization is needed. 2% and 5% damping ratios were used for the analysis. Two hysteresis models were used in the analysis, one was bilinear and the other was stiffness degrading Q-model [15]. 10% strain hardening ratio was used for both hysteresis models. Parametric studies [9] shows that R only slightly dependent on T and roughly equal to μ in the medium-period and long-period region. R strongly depends on T and μ in the short-period region. Influence from damping and hysteretic behavior is moderate in the whole period region.

Riddell [16] used 72 horizontal motions and classified the soil into three types. The analyses showed that the R-μ-T relationship from [16] matches well with the R-μ-T relationship from [8].

The R-μ-T relationship from some previous research [7-9] is shown in Fig. 1 for comparison purpose. Fig. 1a shows the results from [7] and [9] using the same SDOF properties: 5% damping ratio, 10% strain hardening ratio. The predicted R-μ-T relationship in [7] is based on the USA ground motion group. Fig. 1a shows that the predicted R-μ-T relationships are close when μ is small, the difference between the two predictions increases as μ increases. Fig. 1b shows the results from [7] and [8] with very close SDOF properties: 5% damping ratio, 2% strain hardening ratio from [7] and 3% straining hardening ratio from [8]. The prediction from [8] contains two soil sites. Fig. 1b shows that the predictions from [7] and [8] are very close till μ = 4. Difference at μ = 8 is observed, however this difference is not as significant as the difference shown in Fig. 1a. Fig. 1 implies that different R-μ-T relationships may not match each other very closely even the SDOF properties are the same or very close. This difference is probably mainly due to the difference of the earthquake records used in the analyses. However, the predicted R-μ-T relationships follow the same trends: R is nearly constant for medium to long period structures, R increases as T increases for short period structures.

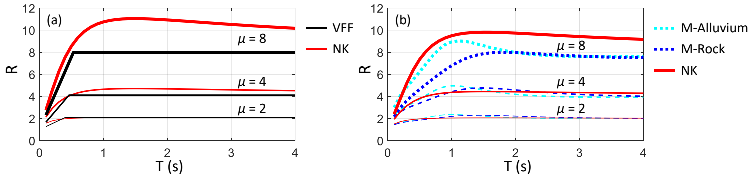

Fig. 1 – R-μ-T relationship from previous research: (a) VFF [9] and NK [7], γ = 10%; (b) M-Alluvium and M-Rock, γ = 3% [8], NK γ = 2% [7].

3. Flexible diaphragm structure and its simplification

Structures with long floor spans possess diaphragms that behave quite flexible [17], such as parking garages. This section will explain the simplification of a structure with flexible diaphragm to a two-degree-of-freedom (2DOF) system (schematically shown in Fig. 2).

Fig. 2a shows a typical plan of a flexible diaphragm, which is supported by shear walls at both ends. If assume the diaphragm is simply supported at two shear walls and the diaphragm density is evenly distributed along the span. The modal mass that is contributed to the diaphragm fundamental period is half of the diaphragm mass. Fig. 2b shows a simplified line model of the flexible diaphragm. Half of the diaphragm mass is lumped at the middle of the line model, the other half of the mass is lumped at the support evenly, which is a quarter of the diaphragm mass at each support. Therefore, the mass is evenly distributed to the diaphragm and shear walls in the 2DOF. Fig. 2c shows the lateral deformation shape of the diaphragm under the fundamental mode. Fig. 2d shows the simplified 2DOF of a structure with flexible diaphragms. The mass and stiffness absolute value do not have influence on R and μ because both R and μ are non-dimensional. The diaphragm stiffness and shear wall stiffness are denoted as k_2 and k_1 respectively in Fig. 2d. A ratio between k_1 and k_2 is used to show the relative diaphragm flexibility, and this ratio is represented by α. α = 0 implies that k_2 is infinite and the structure is a rigid diaphragm structure.

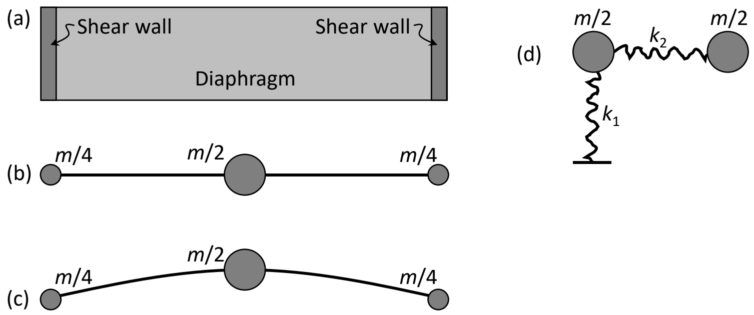

Fig. 2 – Flexible diaphragm: (a) typical plan view; (b) simplified model in plane with mass distribution; (c) deformed shape of the in plane simplified model under earthquakes; (d) 2DOF system.

4. Study parameters and analysis settings

Based on the previous research summarized in Section 1, soil sites, structural periods, ductility ratio, damping ratio, strain hardening ratio have more influence to the R-μ-T relationship. In addition, for the purpose of studying the influence from diaphragm flexibility, relative diaphragm flexibility is also considered.

The structural periods under investigation varies from 0.1 s to 4 s with an interval of 0.1 s. The ductility ratio under investigation varies from one (elastic structure) to eight with an interval of one. The damping ratio under investigation is 5%. The strain hardening ratio under investigation are: 0%, 5% and 10%.

The relative diaphragm flexibility is: 0 (rigid diaphragm structure), 0.25, 0.5, 1, 2, 5, 8, 10.

30 earthquake records from the far field earthquake record list in [18] are used for performing nonlinear time history analyses. These 30 records are the two normal horizontal components recorded at 15 stations from 10 earthquake events listed in Table 1. All records were recorded at Site D (stiff soil sites) according to NEHRP site class classification [19]. The pseudo acceleration spectra of these earthquakes with 5% damping are shown in Fig. 3.

The analysis is performed using OpenSees[1]. k_1 is assumed as 1. k_2, m are changed depending on the relative diaphragm flexibility and corresponding 2DOF fundamental periods. The damping is applied as Rayleigh Damping when $\alpha > 0$. The damping is applied as viscous damping when $\alpha = 0$ (the 2DOF turns to be a SDOF).

The analyses of elastic 2DOF systems (R = 1) are first performed to get the maximum force demand for each 2DOF system under earthquakes. Then, different R (R > 1) are applied to the 2DOF systems to obtain corresponding ductility demands. Finally, corresponding force demand at a given ductility capacity of the 2DOF systems can be obtained.

[1] https://opensees.berkeley.edu/OpenSees

Table 1 – Earthquake records used for analyses

ID No.	Year	Earthquake Name	Recording Station	Magnitude
1	1971	San Fernando	LA – Hollywood Stor	6.6
2	1979	Imperial Valley	Delta	6.5
3	1979	Imperial Valley	El Centro Array #11	6.5
4	1987	Superstition Hills	El Centro Imp. Co.	6.5
5	1987	Superstition Hills	Poe Road (temp)	6.5
6	1989	Loma Prieta	Capitola	6.9
7	1989	Loma Prieta	Gilroy Array #3	6.9
8	1992	Landers	Coolwater	7.3
9	1992	Landers	Yermo Fire Station	7.3
10	1994	Northridge	Beverly Hills - Mulhol	6.7
11	1994	Northridge	Canyon Country - WLC	6.7
12	1995	Kobe, Japan	Shin-Osaka	6.9
13	1999	Kocaeli, Turkey	Duzce	7.5
14	1999	Chi-Chi, Taiwan	CHY101	7.6
15	1999	Duzce, Turkey	Bolu	7.1

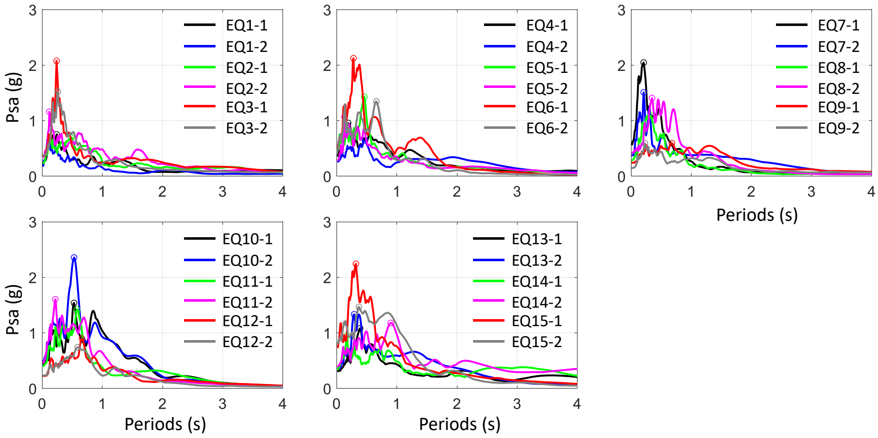

Fig. 3 – Pseudo acceleration response spectra (“-1”, “-2” represent the two horizontal components).

5. Analyses results

All results shown in this section are mean value of analysis results using the 30 earthquake records unless notified.

5.1 Structural ductility from analyses

The ductility is used to indicate the structural inelastic deformation capacity or demand and is defined as the ratio of the maximum deformation (D) and the yield deformation (D_y).

$$\mu = D / D_y \tag{1}$$

The ductility demand of one SDOF (α = 0, rigid diaphragm) and one 2DOF (α = 10) versus different R is shown in Fig. 4. Fig. 4 shows that the ductility demand for both 2DOF and SDOF increases as R increases. The ductility demand of the system is close to constant or slightly decreases for long-period structures. The ductility demand of short-period structures is significantly larger than that of the medium- and long-period structures.

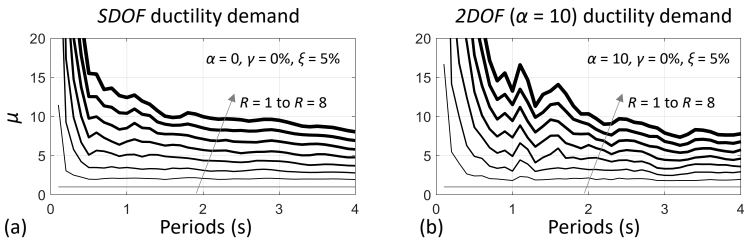

Fig. 4 – Ductility demand vs. R (γ = 0%, ξ = 5%): (a) SDOF; (b) 2DOF (α = 10).

The ductility demand of 2DOF versus different γ is shown in Fig. 5. Fig. 5 shows that the ductility demand decreases as γ increases, implying that structural post-yield stiffness can help reduce the structure deformation demand in earthquakes. However, the influence to R from the post-yield stiffness is not significant.

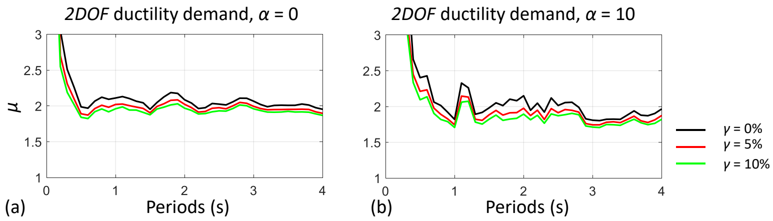

Fig. 5 – Ductility demand vs. γ (R = 2, ξ = 5%): (a) α = 0; (b) α = 10.

The ductility demand of 2DOF versus different α is shown in Fig. 6. Fig. 6 shows that the ductility demand generally increases as α increases for short-period structures. The ductility demand first increases and then decreases as α increases for medium- and long-period structures. This phenomenon is more significant when R is larger. This phenomenon implies that diaphragm flexibility may increase the structural inelastic deformation demand in earthquakes. The ductility demand increment is more significant for a structure with less seismic design strength.

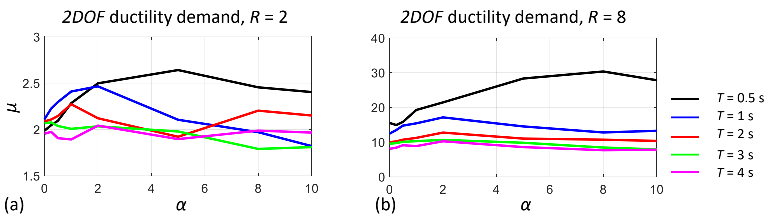

Fig. 6 – Ductility demand vs. α (γ = 0%, ξ = 5%): (a) R = 2; (b) R = 8.

5.2 Structural response modification factor from analyses

The response modification factor is used to determine the minimum seismic design strength of SFRS and is defined as the ratio of the maximum elastic force demand (F) and the corresponding structure yield strength (F_y).

$$R = F / \mathrm{F}_y \tag{2}$$

A comparison on R of the SDOF analyzed in this paper and previous research is shown in Fig. 7. Fig. 7 shows that R from the SDOF analyses in this paper is close to the previous recommended equations when μ is small. The discrepancy between the R from this paper and previous equations [7-9] increases as μ increases. R increases as T increases for medium- and long-period structures when μ = 8, however, the increase of R is not significant in comparison to the increase of R for short-period structures. Fig. 7b shows that when γ = 5%, R from this paper is more close to the equations recommended by Miranda [8] for short- and long-period structures. R from this paper for medium-period structures is more conservative than the equations recommended by Miranda [8] and the equations recommended by Nassar and Krawinkler [7].

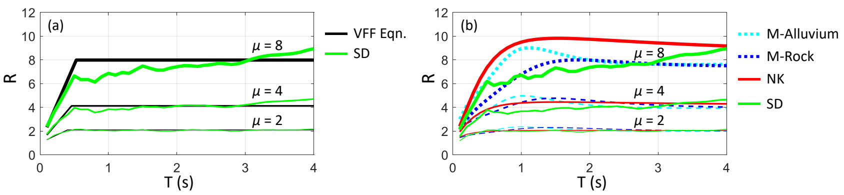

Fig. 7 – R vs. previous research: (a) VFF [9], SD (soil class D), γ = 10%; (b) M-Alluvium and M-Rock, γ = 3% [8], NK γ = 2% [7], SD γ = 5% (soil class D).

R of 2DOF versus different γ is shown in Fig. 8. Fig. 8 shows that R increases as γ increases, meaning that the required SFRS design strength decreases as γ increases. In another word, structural post-yield stiffness can help reduce the required SFRS design strength. However, this difference is not significant.

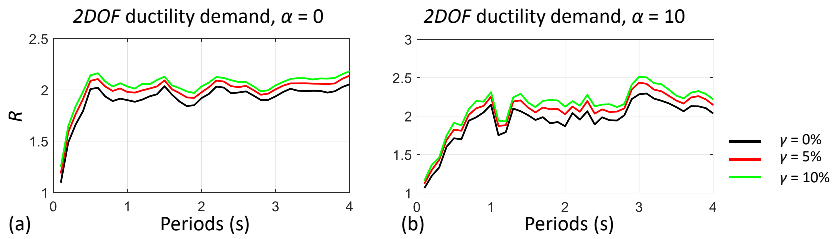

Fig. 8 – R vs. γ (μ = 2, ξ = 5%): (a) α = 0; (b) α = 10.

R versus α is shown in Fig. 9. Fig. 9 shows that R generally decreases as α increases for short-period structures. R decreases and then increases as α increases for medium- and long-period structures. This phenomenon implies that diaphragm flexibility may increase the required SFRS design strength. This phenomenon is also pointed out in [20, 21]. The decrease in R is larger for short-period structure than that for long-period structure.

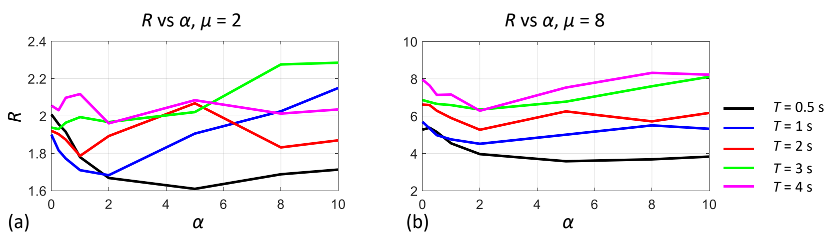

Fig. 9 – R vs. α (γ = 0%, ξ = 5%): (a) μ = 2; (b) μ = 8.

6. Conclusions

This paper summarized previous research on the *R-μ-T* relationships and investigated the influence on the *R-μ-T* relationships from diaphragm flexibility through running parametric nonlinear time history analyses. The results show that:

1. The diaphragm flexibility can increase the structure inelastic seismic deformation demand in comparison to structures with rigid diaphragms.
2. The diaphragm flexibility can increase the required SFRS seismic design strength in comparison to structures with rigid diaphragms.
3. For short-period structures, the response modification factor decreases as diaphragm flexibility increases, meaning that the required SFRS design strength increases as diaphragm flexibility increases.
4. For medium- to long-period structures, the response modification factor decreases first and then increases as diaphragm flexibility increases. This trend may not be clear for structures with small target ductility. This trend becomes more clear for structures with larger target ductility, meaning that for flexible-diaphragm structures with large ductility capacity, the required SFRS design strength may increase for medium-period structures.

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