Influence of concrete behaviour modelling on nonlinear response of oscillators

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Abstract:

A set of 4620 single-degree-of-freedom oscillators have been taken into consideration which has different natural periods, different critical damping ratios and different backbone curves. The initial concrete cracking phenomenon was taken into account in the considered backbone curves. Two sets of ground motion records were also selected to be representatives of free-field and near-field events. The incremental dynamic analysis was performed in order to quantify the seismic demand in different intensity levels. Then, the relationship between natural period, ductility factor and strength reduction factor was derived versus intensity measure. Influence of each input variable was also studied in which revealed that the natural period and the concrete initial cracking have significant influence on the seismic demand of oscillators.

Keywords: Strength reduction factor, ductility, natural period of vibration, nonlinear spectrum, near field, far field.

1. INTRODUCTION

Reinforced concrete structures are one of the most commonly used structures all over the world. However, the high nonlinear behaviour of this kind of structures still needs more research, e.g. to shed light into the effects of nonlinear modelling. One of the most common methods to predict the nonlinear response of concrete structures is the simplified nonlinear spectra in which have been widely recommended in seismic design and rehabilitation regulations e.g. in ATC40 and FEMA 274 [1, 2]. A set of closed-form formulas have been also proposed in this manner to predict the strength reduction factor for a given period and ductility [3, 4, 5, 6, 7, 8 and 9]. It is worth noting that the conventional design and rehabilitation procedures can significantly simplified by using this kind of closed-form formulas.

The aim of this paper is to evaluate the seismic behaviour of a set of 4620 single-degree-of-freedom (SDOF) oscillators, which was taken into account based on their period, damping and nonlinear backbone curve characteristics. Eleven different periods, three damping ratios, five cracking cases, seven ductility ratios, five hardening slopes and two collapse negative slopes were taken into account to cover a wide range of nonlinear behaviour of oscillators. All combinations of nonlinear characteristics with the eleven periods and the three damping ratios produces 4621 different oscillators to be taken into consideration.

The SDOF oscillators were analyzed for two sets of ground motion records which are representative of far and near-field records. The far-field records contain 30 strike-slip records with moment magnitude of 6.5 to 6.9. The records are corresponding to the firm soil without any directivity effects. The near-field set contains 31 strike-slip records corresponding to four different earthquake events. They were all recorded within 16 kilometre of the earthquake epicentre. The incremental dynamic analysis was employed to calculate the system demand ductility in a wide range of earthquake intensity levels. The relationship between the strength reduction factor and the ductility

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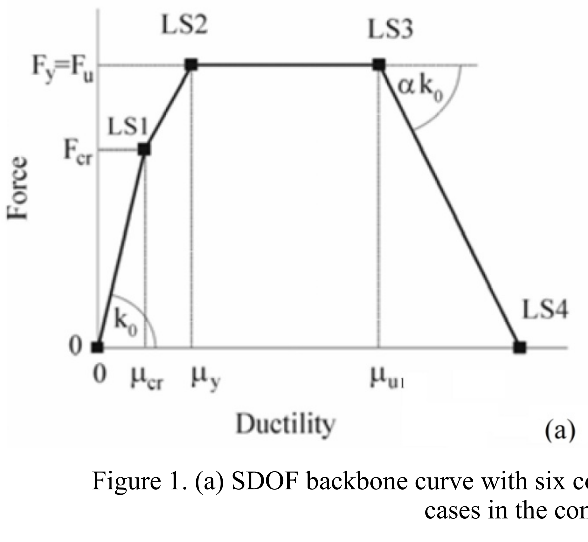
factor was then derived for all considered SDOF systems. The results show that the natural period of vibration as well as the primary concrete cracking can significantly influence on the predicted strength reduction factors.

2. SELECTION OF SDOF OSCILLATORS

A relatively large set of SDOF oscillators were considered with a variety of characteristics. For this purpose, a four segments backbone curve, as shown in Figure 1a, was assumed to be a good representative of concrete Multi-Degree-Of-Freedom (MDOF) systems. The first segment is corresponding to the linear behaviour which lasts at the Limit State No.1 (LS1). The ductility and force corresponding to LS1 are, respectively, μ_{cr} and F_{cr}. The LS1 point is the initiation of cracking phenomenon. The second segment of the backbone curve, as seen in Figure 1a, contains the cracking phenomenon with decreasing trend in the stiffness till LS2 point which represents the yielding point. The ductility and force corresponding to LS2 are, respectively, μ_y =1 and F_y. The third segment in the backbone curve is corresponded to the nonlinear behaviour of the oscillator with the end point of LS3 which is the beginning of the collapse region. The fourth segment (last one) is corresponded to the collapse region with negative stiffness equal to αk_0 till the LS4 point.
The backbone curve is controlled by four controlling parameters, i.e. F_{cr}, F_y , μ_{cr} and μ_y, before LS2 point. By changing of those four parameter, different cracking cases can be obtained as shown in Figure 1b. The following assumptions are also considered for the assumed oscillators:

- Eleven natural periods equal to 0.1, 0.2, 0.3, 0.4, 0.5, 0.75, 1, 1.25, 1.5, 1.75 and 2 s.
- Three critical damping ratios (proportional to mass) equal to 1, 3 and 5 percent.
- Seven μ_{ul}/μ_y cases equal to 2, 3, 4, 5, 6, 7 and 8.
- Two αk_0 cases equal to -0.5 and -0.05.
- Five F_{cr}/F_y cases equal to 0.1, 0.3, 0.5, 0.7 and 0.9.
- Five μ_{cr}/μ_y cases equal to 0.1, 0.3, 0.5, 0.7 and 0.9.
- The Takeda hysteretic behaviour was assumed with β=0.5 [10].

All combinations of the controlling parameters produce 4620 oscillator cases which were analysed for two sets of ground motion records i.e. the near and free-filed records [see 11]. The OpenSees platform was also used to conduct nonlinear response-history analysis [12].



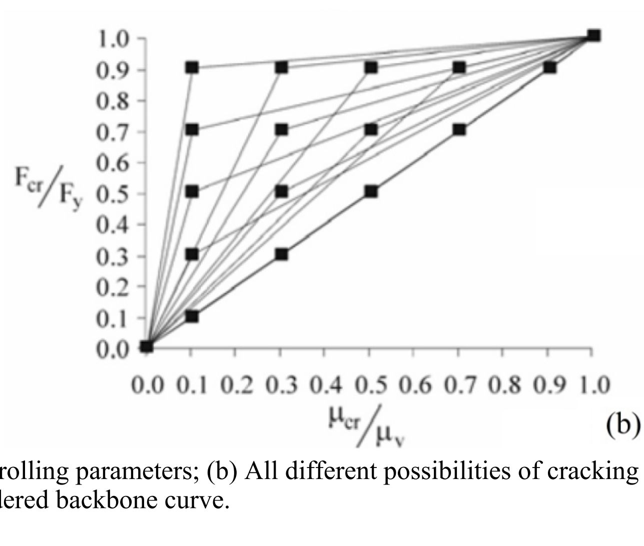


Figure 1. (a) SDOF backbone curve with six controlling parameters; (b) All different possibilities of cracking cases in the considered backbone curve.

3. SELECTION OF GROUND MOTION RECORDS

Two GMR sets are employed in order to conduct the required analyses. The first set contains 30 free filed GMRs as listed in [13]. The source of records can be found in [14]. The records have

moment magnitude between 6.5 to 6.9 which was recorded on firm soil without any directivity effects. The individual spectra and the mean and the mean and the standard deviation spectra ate shown in Figure (2left). Although the magnitude distance variation is relatively limited in the selection process, however, the dispersion in the linear spectra is not negligible.
The second set of records contains 31 strike-slip near-filed records containing directivity effects. All the distances are less than 16 km and recorded on NEHRP [15] S_c or S_d site characteristics. The corresponding linear spectra are shown in Figure (2right) and the detailed information can be obtained in [11].

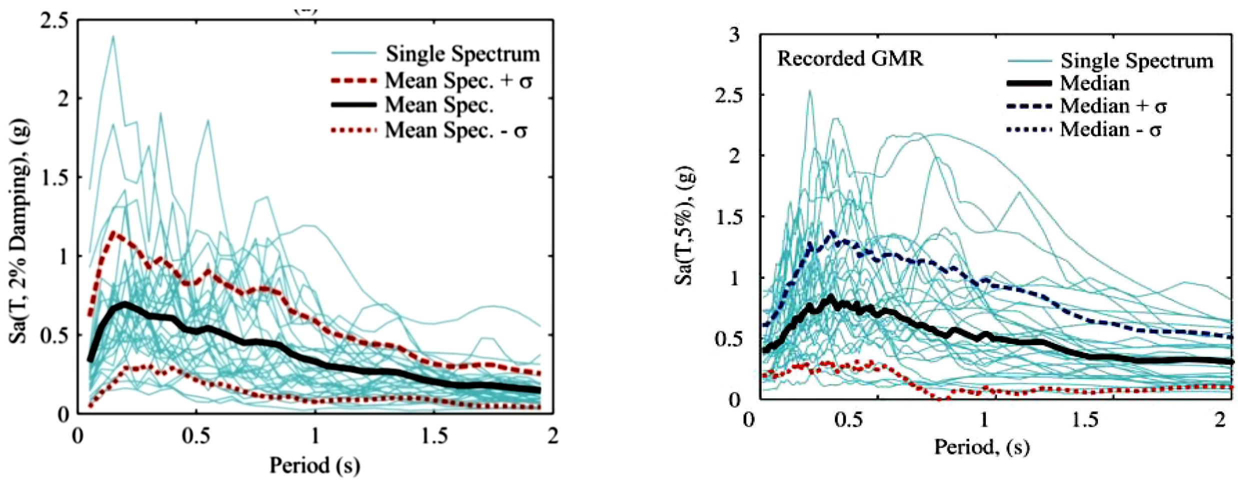


Figure 2. Ground motion records, (left) 30 free-field records spectra; (right) 31 near-field records spectra.

4. INCREMENTAL DYNAMIC ANALYSIS OF OSCILLATORS

Incremental dynamic analysis (IDA) has been employed in order to quantify the oscillators seismic demand in different intensity levels [13]. Twenty points in each individual IDA curve were calculated in which each point is corresponded to a specific hazard level. Therefore, 30 and 31 IDA curves were obtained for each oscillator, respectively, in the case of free and near-field records. The horizontal axis in IDA curves is the Engineering Demand Parameter (EDP) which is ductility demand in the current study i.e. the ductility in LS1 point. The vertical axis in IDA curves represents the Intensity Measure (IM) which was taken as spectral acceleration at the first period of the given oscillator. However, it can easily be converted to the strength reduction factor as mathematically written in Equation (1).

$$R = \frac{S_{ae}}{S_{ay}} \tag{1}$$

where S_{ae} is spectral acceleration at the natural period of a given oscillator and S_{ay} is the yielding acceleration with nonlinear behaviour ($S_{ay} = F_{cr}/m$) and m is the system mass.

The obtained IDA curves can be presented in R-μ coordinates as shown in Figure 3 for a specific oscillator. Therefore, 4620 sets of IDA curves are at hand which are the foundation for further investigations. To simplify, the mean IDA curve (by means of mean strength reduction factor) was calculated at some specific ductility values i.e. 1 to 8 by increment of 0.5. A sample of mean R versus constant ductility is shown in Figure 4.

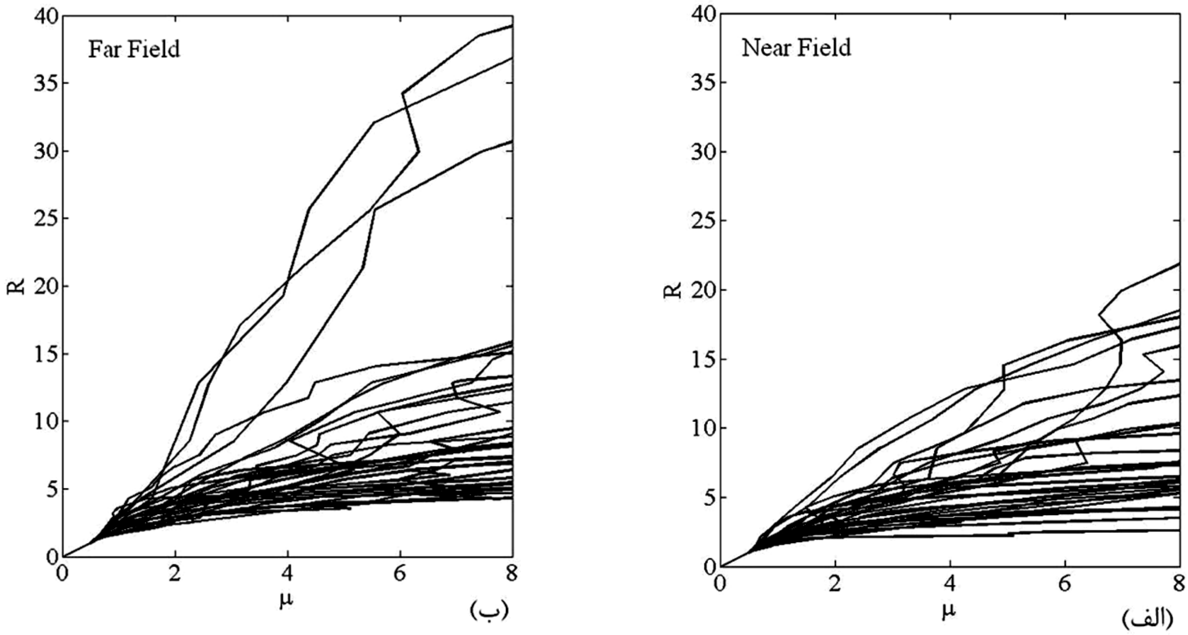


Figure 3. IDA curves in R-μ coordinates for a SDOF oscillator with T=1s, αk0= -0.05, μ_{ul}/μ_y= 5, μ_{cr}/μ_y= 0.5, F_{cr}/F_y= 0.7 and damping=3%, (left) 30 free-field records; (right) 31 near-field records.

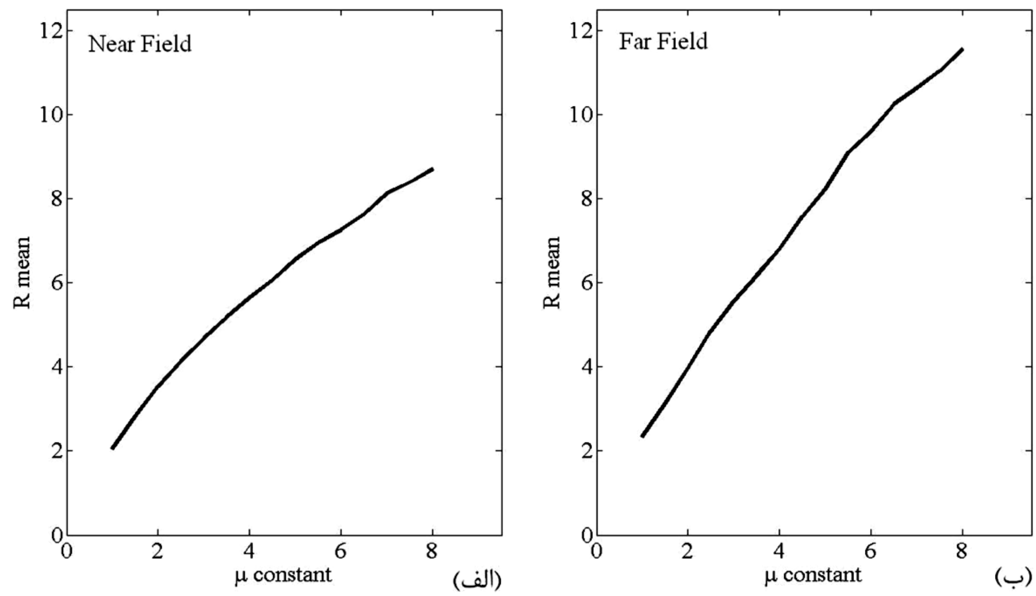


Figure 4. Median IDA curves in R-μ coordinates for a SDOF oscillator with T=1s, αk0= -0.05, μ_{ul}/μ_y= 5, μ_{cr}/μ_y= 0.5, F_{cr}/F_y= 0.7 and damping=3%, (left) 30 free-field records; (right) 31 near-field records.

5. INFLUENCE OF CONTROLING PARAMETERS ON OSCILATORS BEHAVIOUR

The influence of five controlling parameters are investigated in this section.

5.1. Natural period

The influence of natural period in three different critical damping ratio cases are shown in Figure 5 and Figure 6, respectively, in the case of free and near-field ground motion records. As seen in Figures 5 and 6, natural period of oscillators can be accounted as the most important controlling parameter among the others.

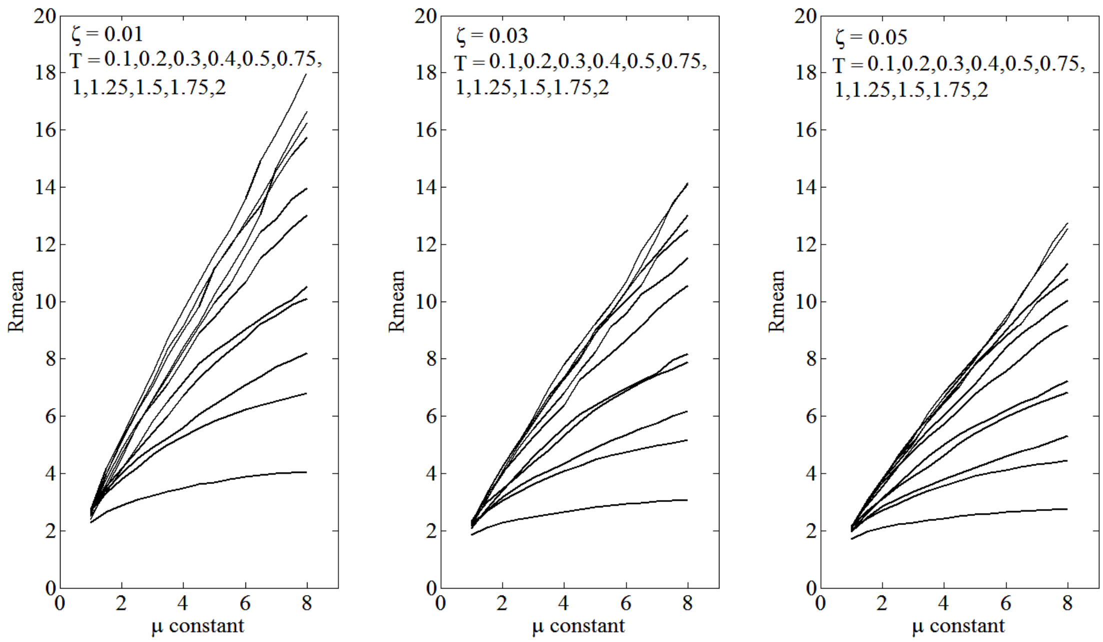


Figure 5. The influence of natural period on mean strength reduction factor versus constant ductility for a SDOF oscillator with αk0= -0.05, μ_{ul}/μ_y= 5, μ_{cr}/μ_y= 0.5, F_{cr}/F_y= 0.7 and free-field records, (a) Damping=1 percent; (b) Damping=3 percent; (c) Damping=5 percent.

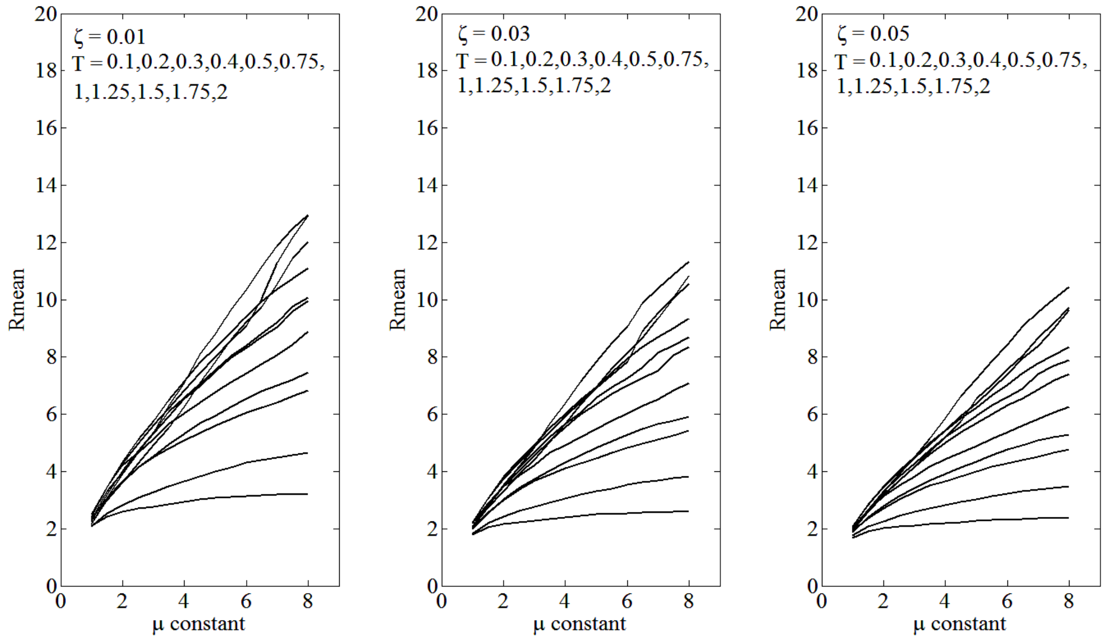


Figure 6. The influence of natural period on mean strength reduction factor versus constant ductility for a SDOF oscillator with αk0= -0.05, μ_{ul}/μ_y= 5, μ_{cr}/μ_y= 0.5, F_{cr}/F_y= 0.7 and near-field records, (a) Damping=1 percent; (b) Damping=3 percent; (c) Damping=5 percent.

5.2. Damping

The influence of damping ratio on the mean strength reduction factor are shown in Figure 7 and Figure 8, respectively, in the case of free and near-field ground motion records. As seen in Figures 7 and 8, this influence is increased by increasing in the considered natural period. Additionally, it seems that the influence of damping ratio is identical in both free and near-field ground motion records.

5.3. αk_0 parameter

The influence of αk_0 parameter on the mean strength reduction factor are shown in Figures 9, 10 and 11 in the case of free-field records and in Figures 12, 13 and 14 in the case of near-field ground motion records. As seen in Figures 9 to 14, the influence of this parameter is negligible in low ductility values. On the other hand this influence is meaningful when the high ductility values were assumed.

5.4. μ_s parameter

The influence of μ_s ($\mu_s = \mu_y / \mu_{cr}$), which is an indicator of system ductility corresponding to LS1 point or in other words ductility in the beginning of cracking region, is shown in Figure 15. As it is obvious in Figure 15, the mean strength reduction factor is increased by increasing in ductility based on both free and near-field records.

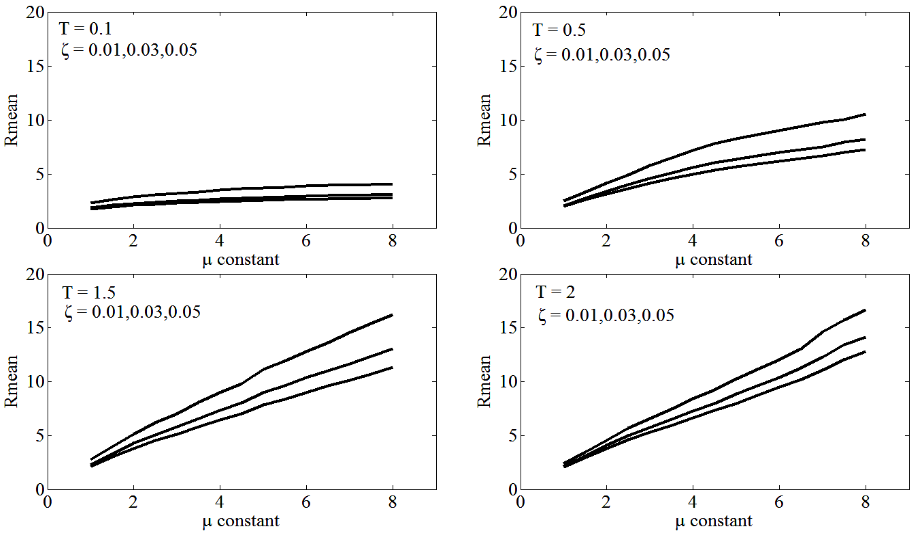


Figure 7. The influence of damping on mean strength reduction factor versus constant ductility for a SDOF oscillator with T=0.1, 0.5, 1.5 and 2s, αk0= -0.05, μ_{ul}/μ_y= 5, μ_{cr}/μ_y= 0.5, F_{cr}/F_y= 0.7 and free-field records.

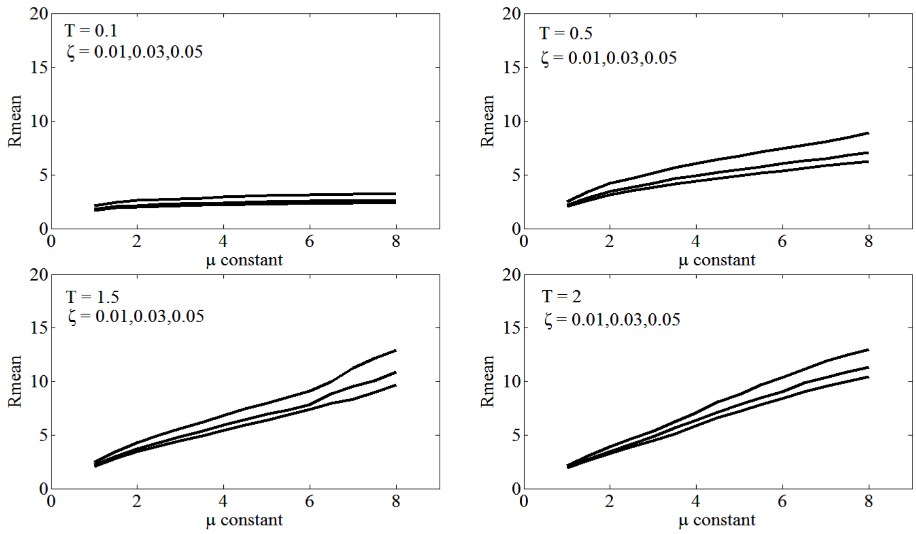


Figure 8. The influence of damping on mean strength reduction factor versus constant ductility for a SDOF oscillator with T=0.1, 0.5, 1.5 and 2s, αk0= -0.05, μ_{ul}/μ_y= 5, μ_{cr}/μ_y= 0.5, F_{cr}/F_y= 0.7 and near-field records.

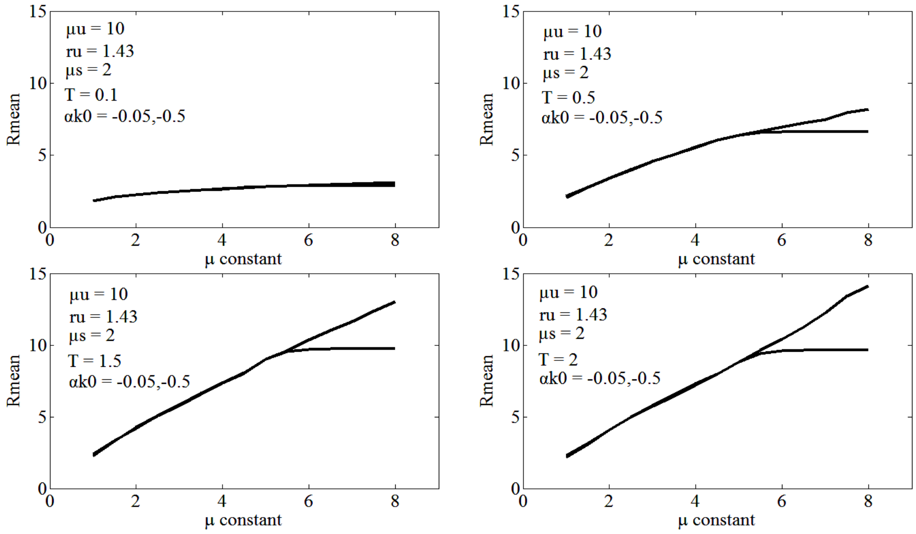


Figure 9. The influence of αk_0 parameter on mean strength reduction factor versus constant ductility for SDOF oscillators with T=0.1, 0.5, 1.5 and 2s, μ_{ul}/μ_y= 5, μ_{cr}/μ_y= 0.5, F_{cr}/F_y= 0.7, damping=3% and free-field records.

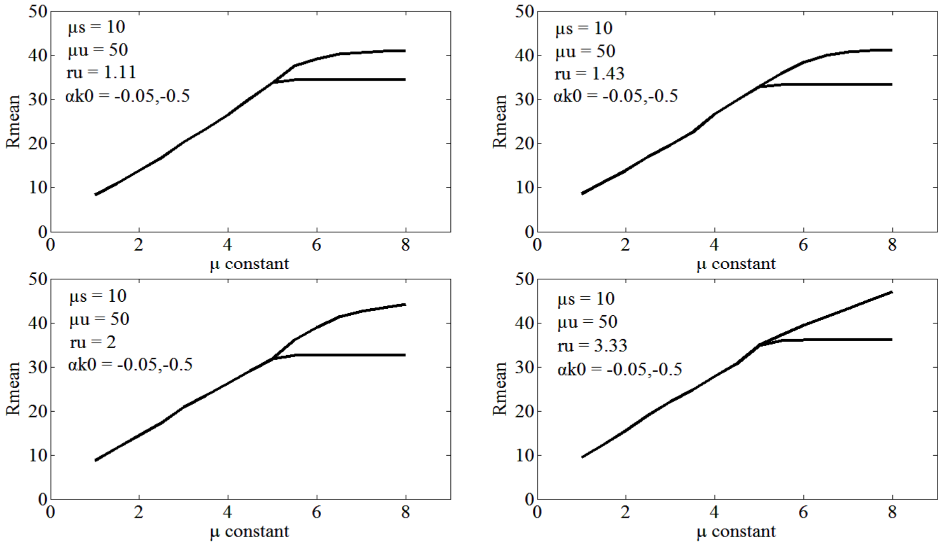


Figure 10. The influence of αk_0 parameter on mean strength reduction factor versus constant ductility for SDOF oscillators with T=1s, μ_{ul}/μ_y= 5, μ_{cr}/μ_y= 0.1, F_{cr}/F_y= 0.3, 0.5, 0.7 and 0.9, damping=3% and free-field records.

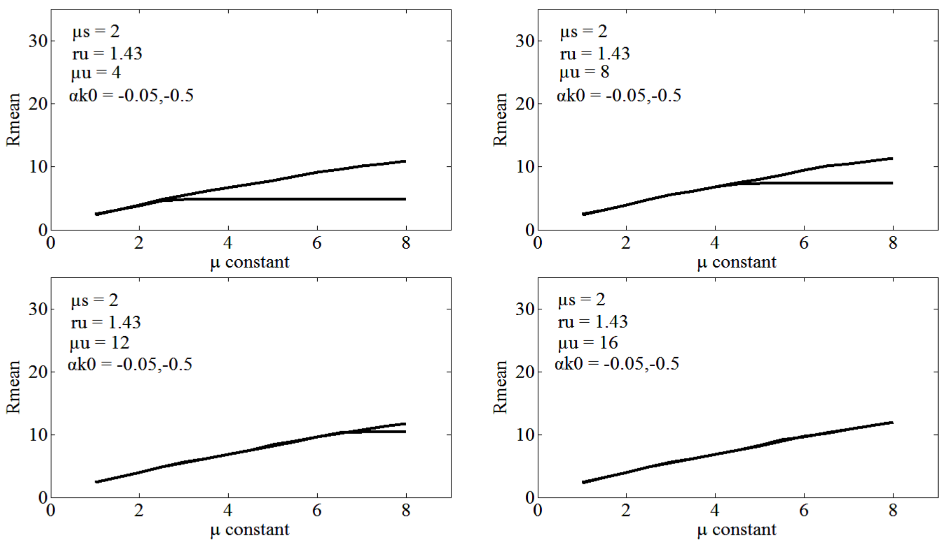


Figure 11. The influence of αk_0 parameter on mean strength reduction factor versus constant ductility for SDOF oscillators with T=1s, μ_{ul}/μ_y= 2, 4, 6 and 8, μ_{cr}/μ_y= 0.5, F_{cr}/F_y= 0.7, damping=3% and free-field records.

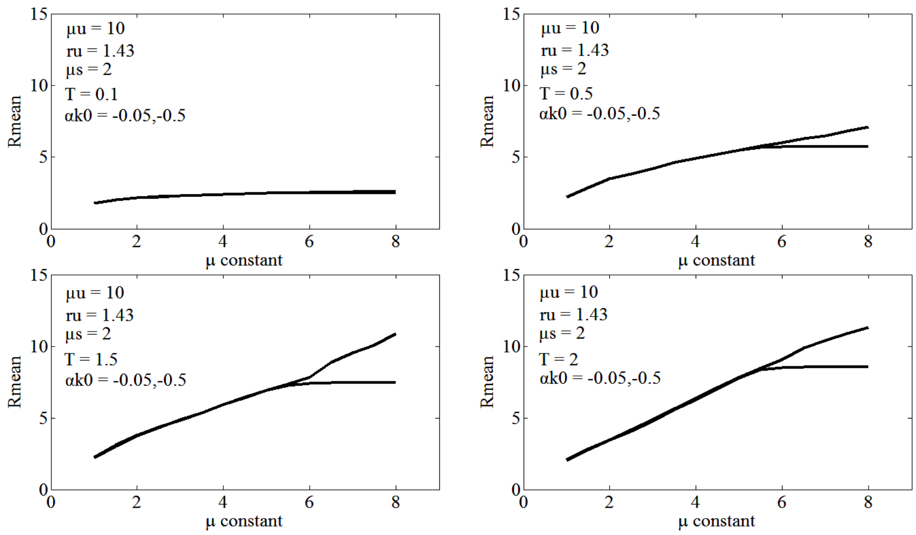


Figure 12. The influence of αk_0 parameter on mean strength reduction factor versus constant ductility for SDOF oscillators with T=0.1, 0.5, 1.5 and 2s, μ_{ul}/μ_y= 5, μ_{cr}/μ_y= 0.5, F_{cr}/F_y= 0.7, damping=3% and near-field records.

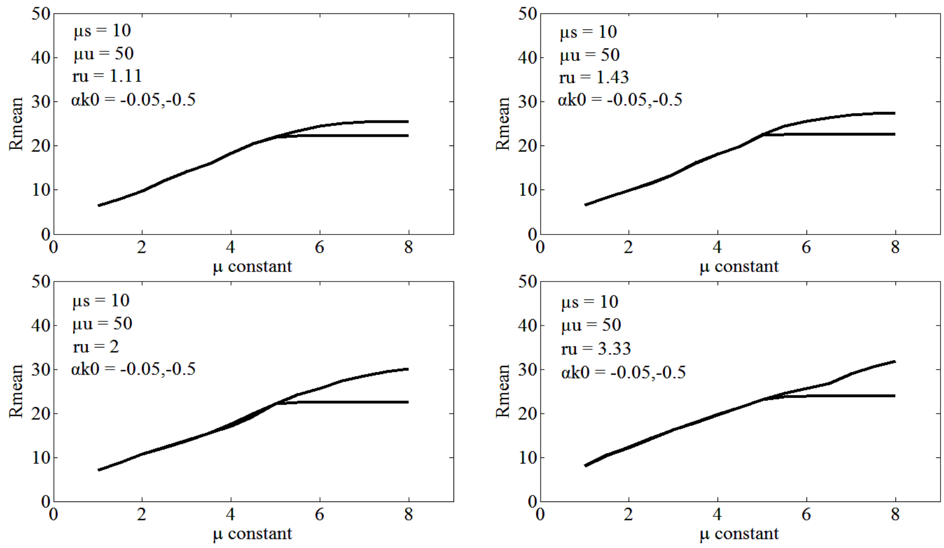


Figure 13. The influence of αk_0 parameter on mean strength reduction factor versus constant ductility for SDOF oscillators with T=1s, μ_{ul}/μ_y= 5, μ_{cr}/μ_y= 0.1, F_{cr}/F_y= 0.3, 0.5, 0.7 and 0.9, damping=3% and near-field records.

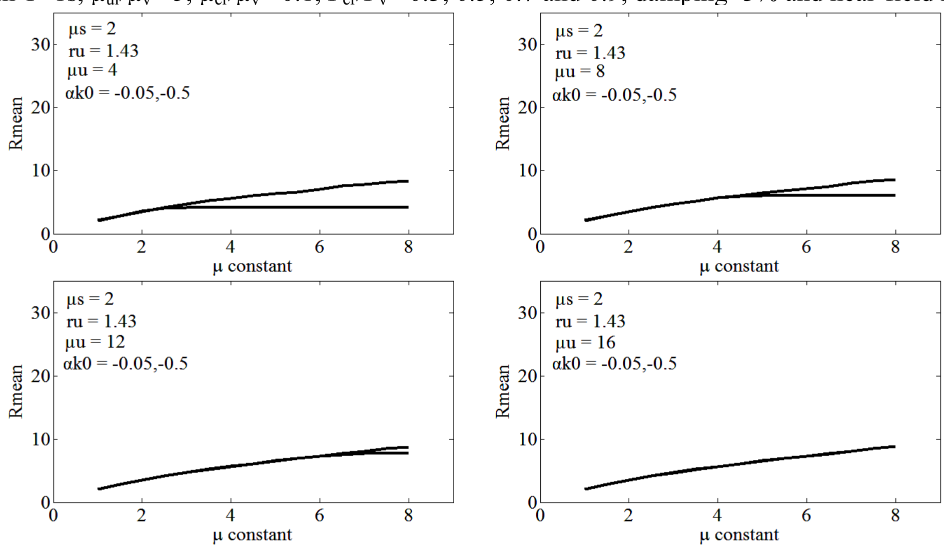


Figure 14. The influence of αk_0 parameter on mean strength reduction factor versus constant ductility for SDOF oscillators with T=1s, μ_{ul}/μ_y= 2, 4, 6 and 8, μ_{cr}/μ_y= 0.5, F_{cr}/F_y= 0.7, damping=3% and near-field records.

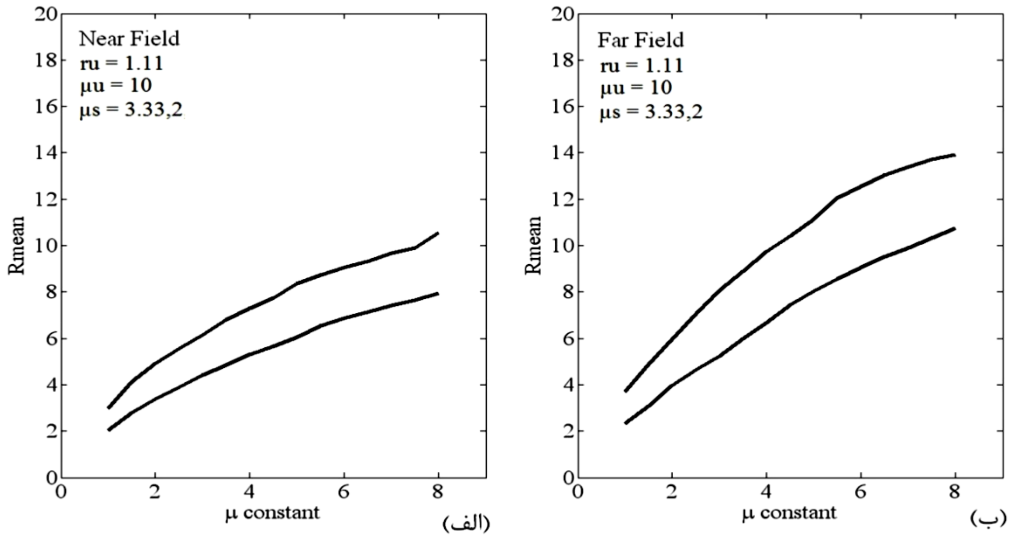


Figure 15. The influence of μ_S parameter on mean strength reduction factor versus constant ductility for SDOF oscillators with T=1s, αk0= -0.05, μ_{ul}/μ_{cr}= 10, F_{cr}/F_y= 0.9, damping=3%, (left) near field records; (right) free-field records.

5.5. μ_u parameter

The μ_u parameter was defined as the ductility at the beginning of strength degradation ($\mu_u = \mu_{ul} / \mu_{cr}$). The influence of μ_u is shown in Figures 17 and 19 in the case of near-filed records and in Figures 18 and 20 in the case of far-filed records. As seen in Figures 17 and 19, at constant r_u and low μ_s values, the influence of μ_u is negligible. However, this influence is meaningful in the range of high μ_s values. This phenomenon can be interpreted that μ_y is low and μ_{cr} is high in the case that μ_s is low. In other words, a relatively long time is needed for cracking initiation, however, it yields quickly. This behaviour is similar to elastic-perfectly-plastic behaviour (near to steel behaviour as seen in Figure 16a, point 1). Therefore, μ_u parameter has not significant influence on R-μ curves. On the other hand, μ_y is high and μ_{cr} is low in the case that μ_s is high. It means that the oscillator cracks quickly but needs a long time to yield. This behaviour is not similar to elastic-perfectly-plastic behaviour (near to concrete behaviour as seen in Figure 16a, point 2). As seen in Figures 17 and 18, the influence of μ_u parameter is significant on on R-μ curves. As an important result, it can be concluded that the initial cracking behaviour modelling is important in the final results. Additionally this effect is existed in both free and near-field ground motion records.
As seen in Figures 19 and 20, at a constant μ_s, the influence of μ_u increases by decrement of r_u. If $F_y=F_u$ assumption is taken into consideration, then, in low r_u values, the F_{cr} is significant (point 2 in Figure 16b) and F_{cr} is not significant in the case of high r_u values (point 1 in Figure 16b). Again the influence of crack modelling is approved is some cases.

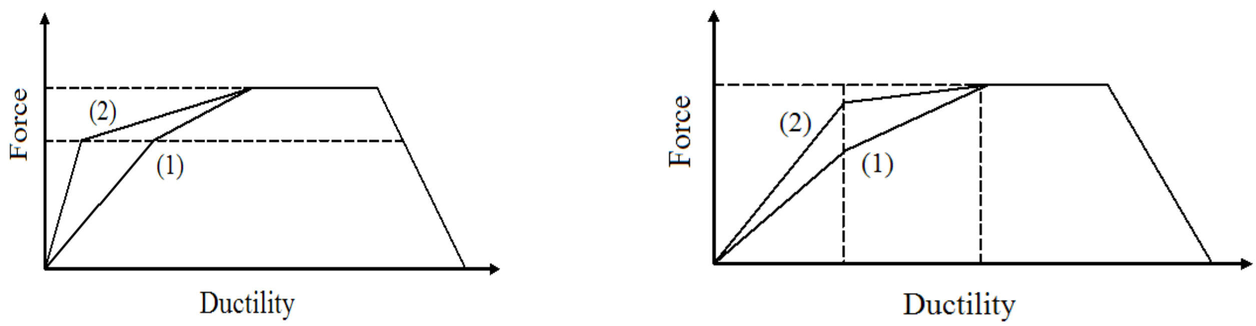


Figure 16. The schematic backbone curve; (a) low μ_S value at point 1 and high μ_S value at point 2; (b) low r_u value at point 1 and high r_u value at point 2.

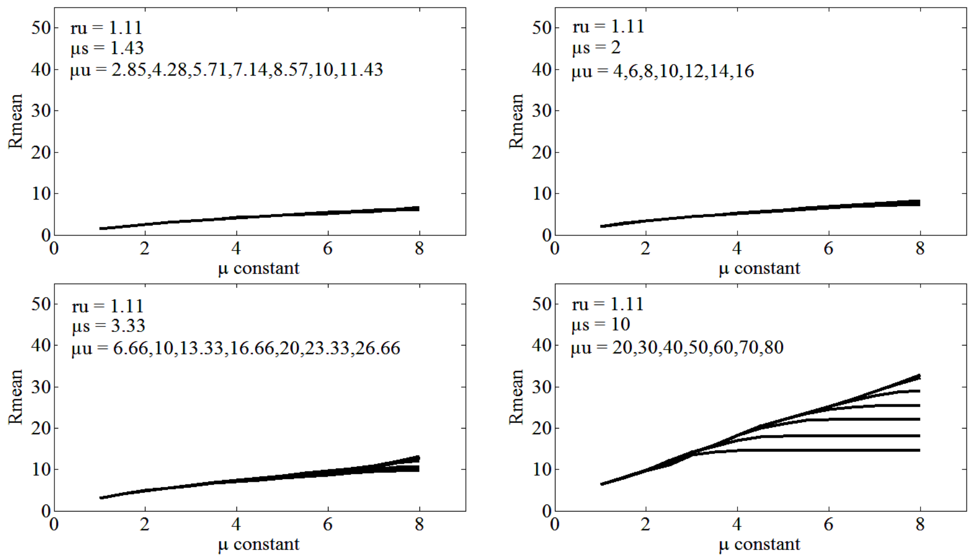


Figure 17. The influence of μ_u parameter on mean strength reduction factor versus constant ductility for SDOF oscillators with T=1s, αk0= -0.05, μ_{cr}/μ_y= 0.1, 0.3, 0.5 and 0.7, F_{cr}/F_y= 0.9, damping=3% and employing 31 near field ground motion records.

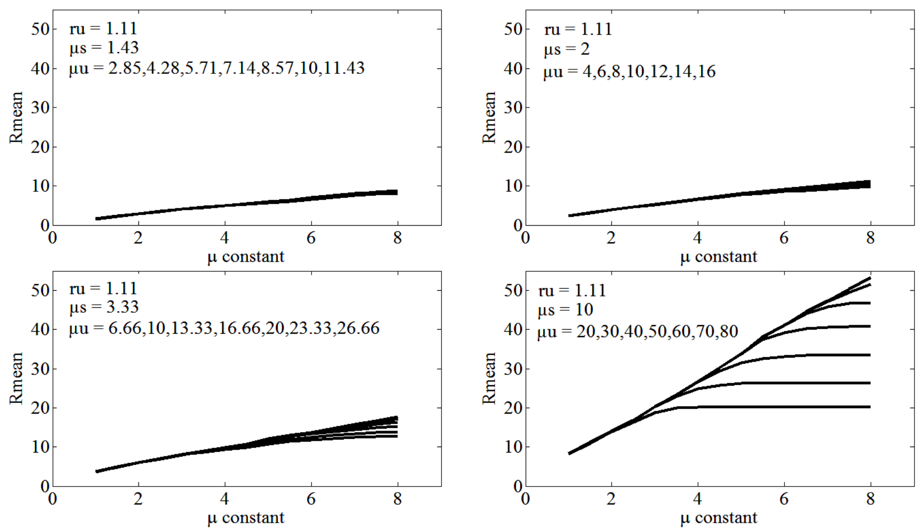


Figure 18. The influence of μ_u parameter on mean strength reduction factor versus constant ductility for SDOF oscillators with T=1s, αk0= -0.05, μ_{cr}/μ_y= 0.1, 0.3, 0.5 and 0.7, F_{cr}/F_y= 0.9, damping=3% and employing 30 free-field ground motion records.

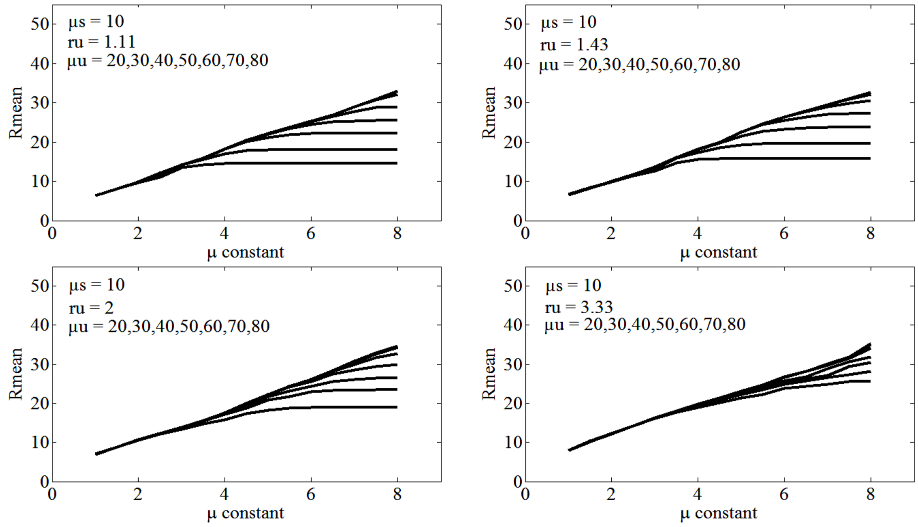


Figure 19. The influence of μ_u parameter on mean strength reduction factor versus constant ductility for SDOF oscillators with T=1s, αk0= -0.05, μ_{cr}/μ_y= 0.1, F_{cr}/F_y= 0.3, 0.5, 0.7 and 0.9, damping=3% and employing 31 near field ground motion records.

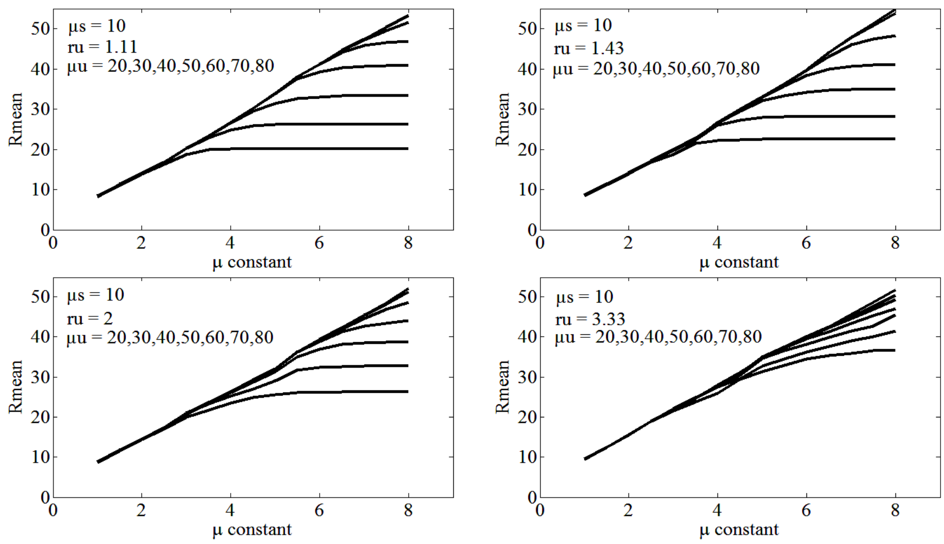


Figure 20. The influence of μ_u parameter on mean strength reduction factor versus constant ductility for SDOF oscillators with T=1s, αk0= -0.05, μ_{cr}/μ_y= 0.1, F_{cr}/F_y= 0.3, 0.5, 0.7 and 0.9, damping=3% and employing 30 free field ground motion records.

6. CONCLUSIONS

A relatively large set of SDOF oscillators were taken into account in order to investigate different SDOF characteristics on R-μ-T behaviour. Four segments backbone curves, including the initial cracking region, were assumed to be good representatives of common concrete buildings. Two sets of ground motion records were taken into account to be representatives of free and near-filed ground motion records. Influence of different parameters are discussed on the obtained R-μ-T curves. The results revealed that the natural period of oscillator plays the most important role in the study. However, as the second governing parameter, the cracking region is influenced significantly on the final R-μ-T curves.

6. ACKNOLEDGEMENTS

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