Effect of base flexibility on demands of the structure

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ABSTRACT: Most of structural engineer model the base of the structure as a fully pinned or fixed base. However, in reality the column base acts as a semi rigid due to the effect of soil, foundation, and base of the column. This paper presents the study about the effect of elastic base flexibility on demands of single storey structures. Dynamic analyses of simple structures with different periods and yielding moment of base by a suite of ground motions indicated that for short and medium period structures, designing of a structure with the short to medium period by assuming that the bases are fixed, underestimates the frame displacement. Moreover, assuming fixed base structure, leads to conservative design of the top moment for medium and long period structures. So, the possibility of formation of the soft storey decreases due to the base flexibility in this range of period. Finally, these findings are verified by the simple kinematic relations that are presented for estimation of demands due to base flexibility.

1 INTRODUCTION

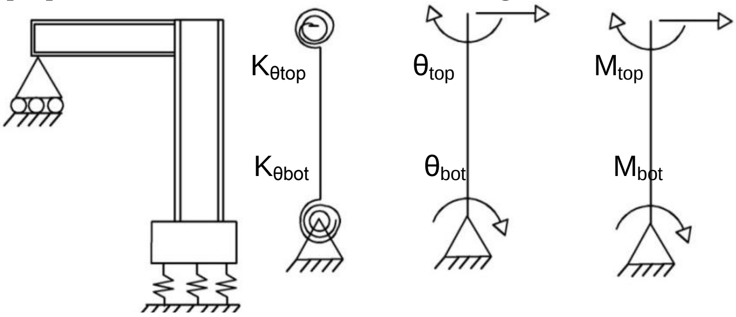
Observations from recent earthquakes show that the performance of the base connections has varied. For example, in the Northridge (1994) and the Kobe (1995) earthquakes many brittle failures were reported at the base level of the structure. In contrast, in the recent Canterbury earthquakes (September 2010, February 2011, and June 2011) there was no significant yielding or fracture damage observed at the base of the buildings, possibly because of the rotational flexibility at the column bases as a result of soft soil. However, some of these buildings were designed assuming rigid bases, where frames expected to yield at column bases as well as over the height of the building due to inelastic mechanism as a result of lateral loading. For this reason a study to assess and develop low damage base connections is being conducted at the University of Canterbury. In the first part of this research the effect of base flexibility on demands of the structure are evaluated. Although some research has been carried out in this area ((Aviram et al., 2010), (Maan and Osman, 2002)), they have considered only a few structures, and those results could not be easily generalized. Furthermore, structural engineers need simple relations for estimation of demands of structures due to base flexibility that cannot be found in these studies. The results of this paper can be used for estimation of demands at the base of the structure especially to develop low damage base connection. Some studies have been carried out to propose low damage base connections ((Midorikawa et al., 2006);(Ikenaga et al., 2006);(MacRae et al., 2009), (MacRae et al., 2010)), but modifying of available low damage bases and developing new types with low damage devices are needed.

This paper aims to answer the following questions:

1. What is the effect of base flexibility on the displacement, base rotation and the moment demand of the top of the columns for single storey structures with a specified rotational flexibility at the top and base of the column and a column base strength level for different periods based on response history analysis?
2. Can simple relationships be developed to estimate the demands level in (1)?

2 ANALYTICAL MODEL

The modelled steel frame has three degrees of freedom with storey height of 3.5m. The top and base flexibilities are varied between fully fixed to fully pinned. Mass of the frame is varied based on period of the structure. The properties of the structure are shown in Figure 1.

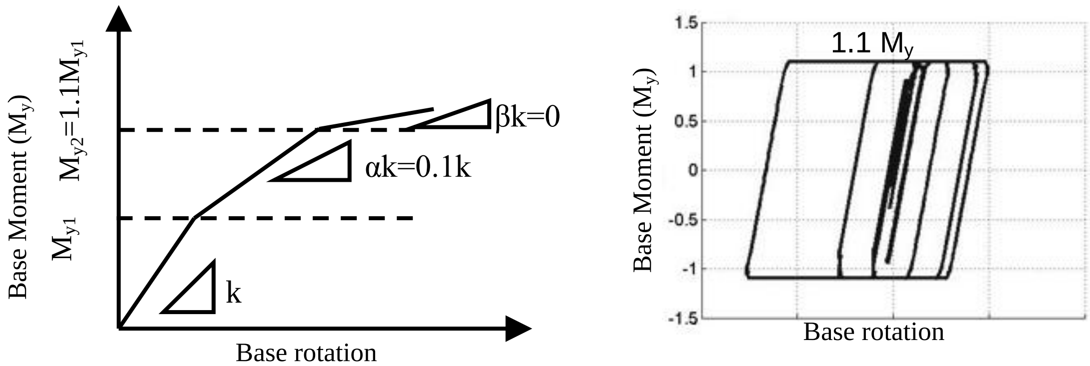


(a) Column (b) Springs (c) DOF (d) Forces

Figure 1: Simple model of the structure

The damping ratio is equal to 5% and the elastic modulus of the structure is 2.1×10^{8} kN/m^{2}, and the second moment inertia of the section assumes $3.5\times10^{-4}m^{4}$. Furthermore, the axial stiffness of the frame was assumed at the high value.

Top and base rotational stiffness are normalized to the *EI/H* of the column. Three different rotational stiffnesses were considered. These were corresponding to the fully pinned condition, 5*EI/H*, *2000EI/H* approximating the fully fixed condition. In order to evaluate nonlinear base rotation, nonlinear time history analysis has been conducted by assuming the Menegotto-Pinto hysteretic curve at the base of the structure. Figure 2 shows that the yielding response due to the loading in the first half cycle of the seismic loading. According to Figure 2a, the slope *αk* only exists during this loading cycle. For subsequent cycles, the stiffness decreases from *k* to *βk*. This may be seen in the cyclic response of Figure 2b.



(a) Idealized loading response for first half cycle (b) Cyclic response

Figure 2: Menegotto-Pinto hysteretic loop

Time history analysis was carried out using the twenty medium suite earthquake records (La 10 in 50) from the SAC steel project for Los Angeles with a probability of 10% in 50 years. The elastic spectral displacement for a wide range of periods is shown in Figure 3.

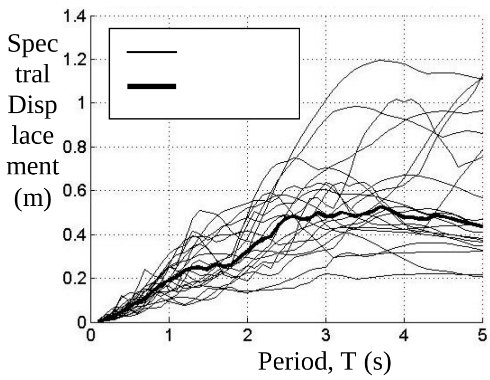


Figure 3: Median and record displacement response spectrum for SAC La 10 in 50 suite

3 EFFECTS OF BASE FLEXIBILITY

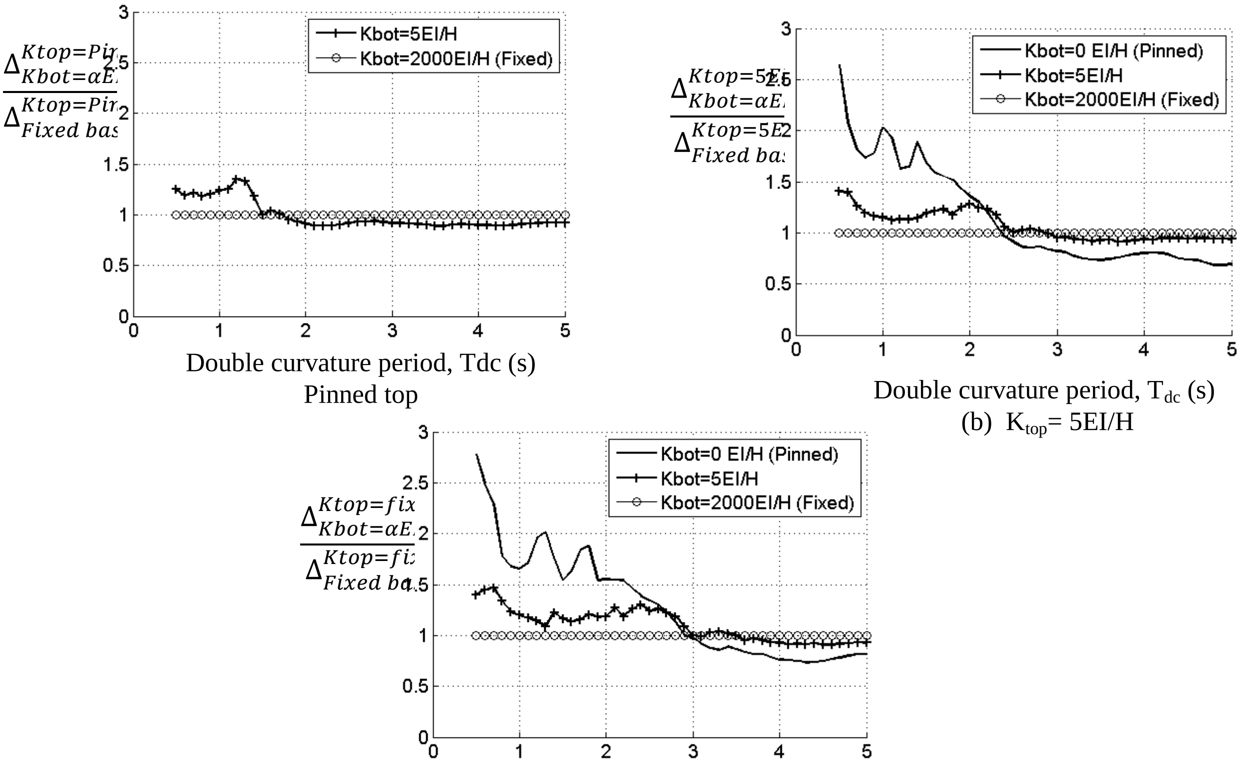
3.1 Linear Analysis

3.1.1 *Time history linear analysis*

Time history linear analysis was carried out by MATLAB software. The periods of the structure given in Figure 4 were the double curvature period, T_{dc}, computed as a column lateral stiffness of $12EI/L^3$, assuming the column was fixed rotationally at the top and bottom and deflection is double curvature. The data points in Figure 4 were calculated based on the following steps:

1. The double curvature period was estimated.
2. The boundary conditions (top and base flexibilities) for the structure were applied. For example, when K_{top} is *5EI/H* and K_{bot} is *2000EI/H*, a top rotational spring provides this stiffness (*5EI/H*), for the fixed base structure.
3. Response history analysis (*RHA*) was conducted to determine derived response quantities. It should be noted that the fundamental period was greater than the given by T_{dc}. For the fixed top structure with the base flexibilities of *0.EI/H, 5EIH, 2000EI/H* the period was increased by *2.0*, *1.22* and *1.0* times related to the T_{dc}.

Figure 4 shows the ratio of the lateral displacement with top and base flexibility ($\Delta^{Ktop=\beta EI/H}_{Kbot=\alpha EI/H}$) to the displacement of the fixed base structure with a given top flexibility ($\Delta^{Ktop=\beta EI/H}_{Kbot=Fixed}$). These results are presented based on the median response for the twenty earthquakes. The *P-Δ* effects were not considered in the preliminary analysis.



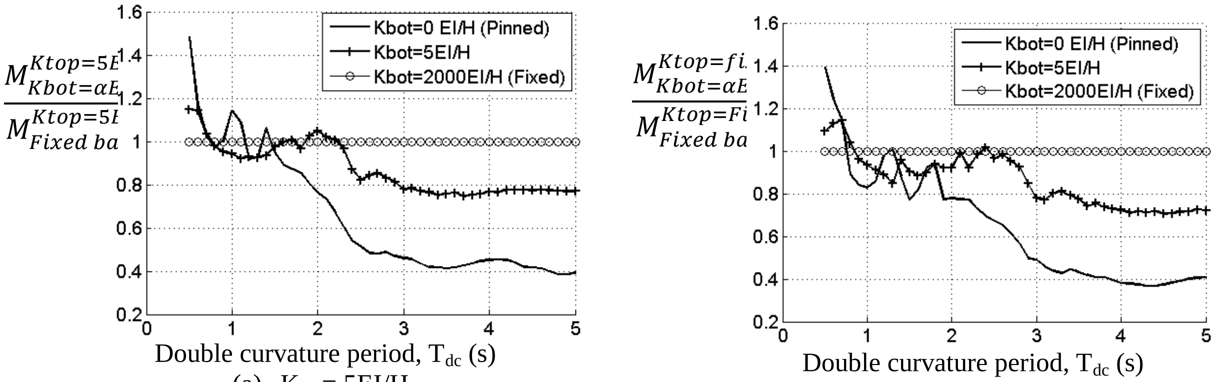
Double curvature period, T_{dc} (s)

(c) Fixed top

Figure 4: Base flexibility effect on elastic top displacement of columns with top flexibilities of 0 EI/H (pinned), 5EI/H and 2000 EI/H (fixed)

It may be seen that for structures with $T_{dc} < 3s$, which is the majority of realistic structures, the lateral displacement increases due to the increase of rotational flexibility. This is consistent with **Figure 3** which also indicates as average increase in displacement over this range and a smaller change in displacement for larger periods. So, designing of a structure with the short to medium period by assuming that the bases are fixed, underestimates the frame displacement.

Figure 5 shows that the moment demands at the top of the column considering base flexibility for top rotational spring flexibility of *5EI/H* ($M_{Kbot=\,\alpha EI/H}^{Ktop=5EI/H}$) and high rotational stiffness ($M_{Kbot=\,\alpha EI/H}^{Ktop=Fixed}$) respectively, are greater than those assigned the fixed base ($M_{Kbot=\,Fixed}^{Ktop=5EI/H}$), ($M_{Kbot=\,Fixed}^{Ktop=Fixed}$) respectively when the double curvature period, T_{dc}, is less than about *0.8s*. This indicates that as the top moment is increased for $T_{dc}<0.8s$, there is more likelihood of a soft-storey mechanism due to base flexibility. In contrast, for the structures with the double curvature period, T_{dc}, higher than 0.8s, the top moment demands of the column considering base flexibility for top rotational spring flexibility of *5EI/H* and high rotational stiffness respectively, are lower than those assigned the fixed base. So, assuming bases of a structure as the fixed bases, leads to conservative design for the top moment of this period range of the structure. Furthermore, the possibility of formation of the soft storey decreases due to the base flexibility in this range of period.



(a) K_{top}= 5EI/H

(b) Fixed top

Figure 5: Base flexibility effect on elastic top moment of columns with top flexibilities of 5EI/H and 2000 EI/H (fixed)

3.1.2 *Kinematic relation for estimation of demands of the structure with base flexibility*

A simple relationship to estimate the change in response due to the base flexibility is as follow:

Step 1: The change in the period as a function of structural properties like base flexibility: The top rotation degree of freedom is eliminated by making the top fixed. The force- displacement relation is given in Eq. (1). In this equation V is lateral earthquake load, M is the external moment that is applied to the structure (equals to zero).

$$\begin{pmatrix} V \\ M=0 \end{pmatrix} = \begin{pmatrix} k_{11}=\dfrac{12EI}{H^3} & k_{12}=\dfrac{-6EI}{H^2} \\ k_{21}=\dfrac{-6EI}{H^2} & k_{22}=\dfrac{4EI}{H}+K_\theta \end{pmatrix} \times \begin{pmatrix} \Delta \\ \theta \end{pmatrix} \tag{1}$$

So, the relation between the lateral force (*V*) and the displacement (*Δ*) can be calculated by the first row of the Eq. (1). This is given in Eqs. (2) and (3).

$$V = k_{11}\Delta + k_{12}\theta \Rightarrow V = \left[k_{11} - \frac{k_{12}k_{21}}{k_{22}} \right] \times \Delta \tag{2}$$

$$K_{lateral} = \left[12 - \left(\frac{36}{4+\dfrac{H \times K_\theta}{EI}} \right) \right] \frac{EI}{H^3} \tag{3}$$

So, the modified period due to the base flexibility can be calculated by the modified stiffness of Eq. (3).

Step 2: The change in the response due to change in the period: The lateral displacement can be obtained from the elastic response spectrum of the given earthquake based on the modified period. Also, the relation between the displacement (Δ) and the base rotation (θ) can be obtained from solving the second row of the matrix in Eq. (1), that is calculated in Eqs. (4) and (5).

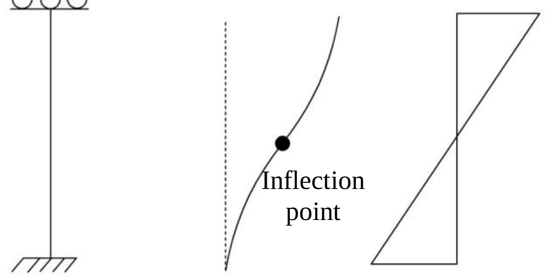
$$M = k_{21}\Delta + k_{22}\theta = 0 \Rightarrow \theta = -\frac{k_{21}}{k_{22}} \times \Delta \tag{4}$$

$$\theta = \frac{6}{H\left(4 + \frac{HK_{\theta}}{EI}\right)} \times \Delta \tag{5}$$

3.1.3 *Interpretation for demands*

For a fixed-fixed structure with a period, T_f such as that shown in Figure 6a, the deformed shape and the bending moment diagrams are similar to those in Figure 6b and Figure 6c respectively.

$$K = \frac{12EI}{L^3} \qquad M_{top} = \frac{VH}{2} = \frac{6EI}{H^2} \times \Delta_{top}$$

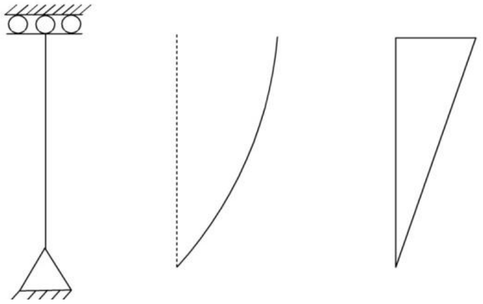


(a) Structure (b) Deformed shape (c) BMD

Figure 6: The fixed-fixed structure

If the base flexibility is such that the structure is fully pinned at the base, as shown in Figure 7 then the structure deformation and bending moment diagram become that shown in Figure 7b. The lateral stiffness is 3EI/L3, and the BMD is shown in Figure 7c. Since the lateral stiffness decreases four times, the structural period doubles.

$$K = \frac{3EI}{L^3} \qquad M_{top} = \frac{VH}{2} = \frac{3EI}{H^2} \times \Delta_{top}$$



(a) Structure (b) Deformed shape (c) BMD

Figure 7: The pinned base-fixed top structure

According to the two above figures, the ratio of top moment of the pinned base to the fixed base structure that is fixed at top is given in Eq. (6).

$$M_{topratio} = \frac{M_{top,pinned\ base}}{M_{top,fixed\ base}} = \frac{1}{2} \times \frac{\Delta_{pinned\ base}}{\Delta_{fixed\ base}} \tag{6}$$

For example, for the structure with the period of 1.0s in Figure 4(c) the top displacement of the pinned base structure (*$\Delta_{pinned\ base}$*) is 1.64 times that of the fixed base structure (*$\Delta_{fixed\ base}$*). According to the Eq. (6), $M_{top\ ratio}$ is 0.84. Moreover, Figure 5 (b) shows that for the period of 1s, this ratio is equal to 0.84 that is consistent with the kinematic method.

For linear increasing elastic spectral displacement diagram such as that used in many design codes for low periods (less than 0.7 seconds from the spectra in NZS 1170.5) the doubling of period corresponds to a doubling of displacement at the top of the column. This results in top moment increases due to the base flexibility and either increasing the possibility of formation of the soft story. This is consistent with Figure 5 for structures with short periods. However, as it is obvious from Figure 3, linear increasing of spectral displacement only matches to the short period structures, and the spectral displacement does not change or decreases for medium and long period structures since the period increases. So, the top moment does not greater than the fixed base structure, and the soft story mechanism is not possible to form except perhaps when the *P-Δ* effects are concluded. So, for medium to long period structures the top moment does not increase relative to the fixed base structure for increasing base flexibility, and the soft story mechanism is not possible to form except perhaps when the *P-Δ* effects are concluded.

3.2 **Nonlinear analysis**

For nonlinear structures, it is positive to estimate the change in inelastic rotation demand, θ, at the base of the structure as well as the response parameters such as the top displacement that affects non-structural elements, and the moment at the top of the column affects the possibility of soft storey mechanism. So, time history nonlinear analysis has been carried out by MATLAB for the structure that was shown in Figure 1. Top rotational stiffness is assumed fixed and base yielding moment is normalized to the maximum elastic base moment of the fixed base structure. Approximate inelastic demand relationship between displacement of the nonlinear structure ($\Delta_{inelastic}$) and displacement of the elastic structure ($\Delta_{elastic}$) is given in Eq. (7).

$$\Delta_{inelastic} = \Delta_{elastic} \times \textit{Modification factor (Mf)} \qquad (7)$$

This modification factor can be calculated as Eq. (8).

$$Mf = \frac{\mu}{R} \qquad (8)$$

Where ductility (μ) and reduction factor (R) can be obtained from the following equations: The relation between ductility and reduction factor is mentioned in many documents such as NZS1170.5 (2004) where for stiff sites (type A,B,C and D) equals Eq. (9). Figure 8 compares the total displacement of the nonlinear model to the displacement of elastic model for NZS method and nonlinear time history analysis. Each point represents the median results of the twenty earthquakes.

$$\begin{cases} R = \mu & T_1 \rangle 0.7s \\ R = \dfrac{(\mu - 1)T_1}{0.7} + 1 & T_1 \rangle 0.7s \end{cases} \qquad (9)$$

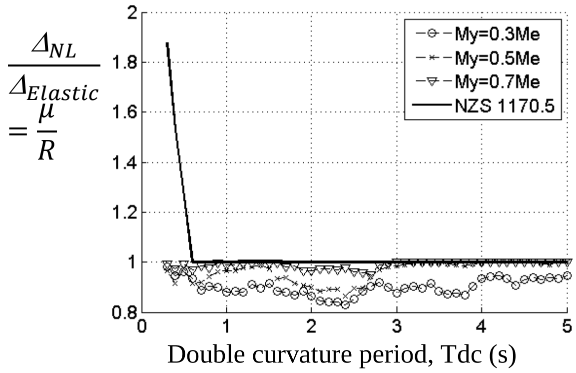


Figure 8: Total displacement of the nonlinear model to the displacement of the elastic model for the structure with Kυbase = 5EI/H and fixed at top

This figure indicates that for different levels of the base yielding and periods of the structure, the code estimation is reasonable, except for very short period structures, that the code approach is conservative for short period structures. Total displacement results from lateral deflection of the column and the total elastic and nonlinear base rotation. So, another method that can be evaluated in parallel to the design guideline method for estimation of nonlinear base rotation is dividing of total displacement to the height of the frame. The accuracy of this method increases as the participation of the column flexural movement to the final displacement reduces. In Figure 9 the base rotation of time history nonlinear analysis is compared with methodology of NZS 1170.5 and also the second method which the total displacement is resulted from only the base rotation *(Δ_{top}/h)* for three different yielding moment levels. Each point represents the median results of the twenty earthquakes.

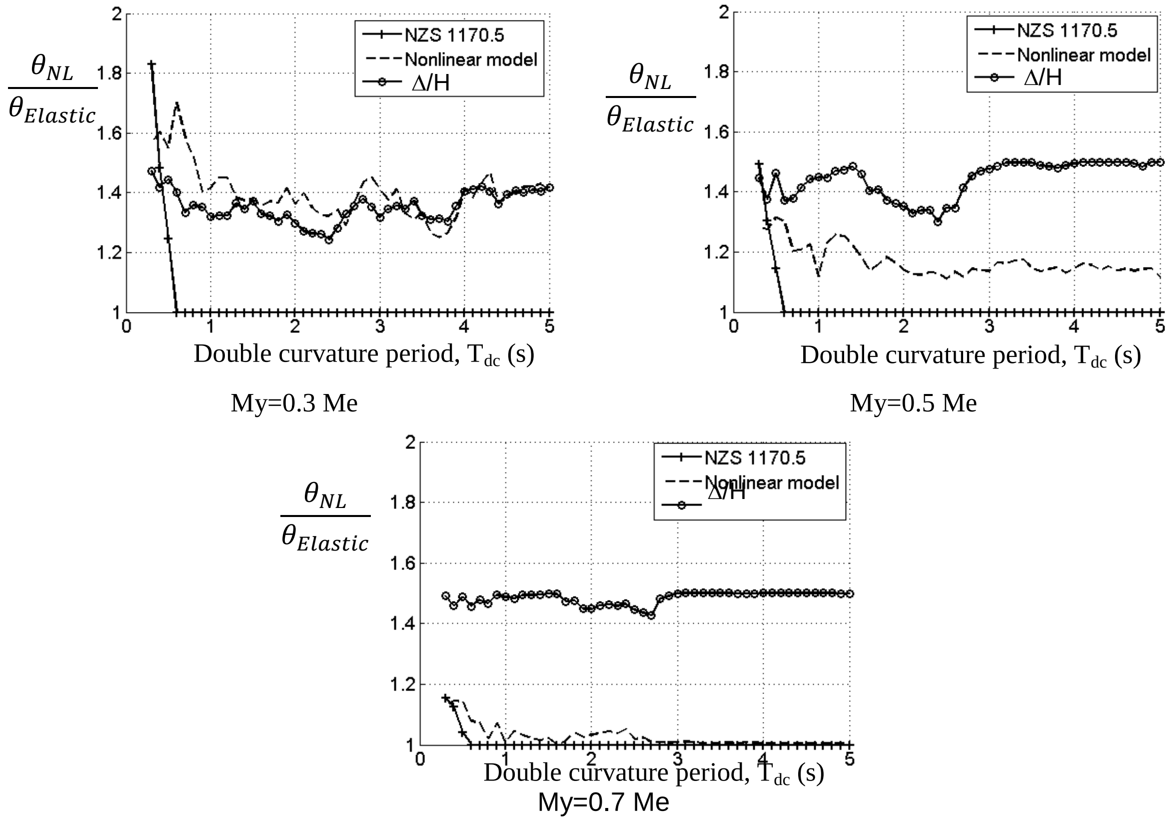


Figure 9: Total base rotation of the nonlinear model to the base rotation of the elastic model for the structure with Kυbase = 5EI/H and fixed at top

Figure 9 indicates that for the lower yielding moment ($M_y=0.3\text{-}0.5M_{elastic}$), due to the high nonlinear rotation at the base, the participation of lateral deflection of column in total displacement of the structure reduces and the total displacement that is divided to the height of the frame shows more exact estimation than the methodology in design guidelines. In contrast, as yielding moment increases ($M_y \geq 0.7\ M_{elastic}$), nonlinear base rotation reduces and it leads to more participation of lateral deflection of column in total displacement of the frame. For this range of base yielding, the prescribed methodology provides more precise estimation. The below step by step methodology is proposed to consider the effect of base nonlinearity to calculate demands due to base flexibility.

Step 1: Calculate the top displacement, base rotation and top moment based on the methodology for elastic section.

Step 2: Calculate ductility (μ) based on reduction factor (R), according to the relation in NZS 1170.5 (2004). (Eq.(9))

Step 3: Calculate the displacement from Eq. (7).

Step 4: The nonlinear base rotation is the elastic base rotation ($\theta_{elastic}$) multiplied by ductility (μ) for high values of the base yielding moment ($M_y>0.7M_{elastic}$). For the lower base yielding moment ($My<0.7M_{elastic}$), the base rotation equals to the total displacement from step 3, that is divided by height of the frame (*H*).

4 CONCLUSION

This paper describes the base flexibility effect on demands of one story steel structure with linear and nonlinear time history analyses. It was shown that:

1. It may be seen that for structures with $T_{dc} < 3s$, which is the majority of realistic structures, the lateral displacement increases due to the increase of rotational flexibility. So, designing of a structure with the short to medium period by assuming that the bases are fixed, underestimates the frame displacement. The moment demands at the top of the column considering base flexibility are greater than those assigned the fixed base when the double curvature period, T_{dc}, is less than about $0.8s$. This indicates that, there is more likelihood of a soft-storey mechanism due to base flexibility of this range of period. In contrast, for the structures with the double curvature period, T_{dc}, higher than 0.8s, the top moment demands of the column considering base flexibility are lower than those assigned the fixed base. So, assuming bases of a structure as the fixed bases, leads to conservative design for the top moment of this period range of the structure. Furthermore, the possibility of formation of the soft storey decreases due to the base flexibility in this range of period.

2. The simple relations were introduced to estimate demands on the structure for the base flexibility. They could also estimate displacement of the elastic structure and the structure with nonlinear bases. Moreover, level of the base yielding moment determines the participation of lateral deflection of the column to the total displacement, so this value determines which of the described methods are more accurate to estimate the nonlinear base rotation.

5 ACKNOWLEDGEMENTS

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