Nonlinear seismic response of structural systems having vertical irregularities due to discontinuities in columns

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SUMMARY: (10 pt)
In the present study effects of the structural irregularity which is produced by the discontinuity of a column in a plane frame subjected to seismic loads including the gravity loads is investigated. Investigation is carried out by adopting the linear and the nonlinear static and dynamic analyses of the structural system such as, the pushover analysis and the analysis in the time domain by considering various seismic records compatible with the spectrum provided in the Turkish seismic code. The study involves a large number of numerical analysis by considering the plane frame structural systems having a specific height and span geometries. However, various types of column discontinuity are taken into account in the analyses. Results of the numerical analysis are presented including the variation of the normal force in the column to identify the load path in the structural system, the pushover curves to recognize the inelastic weakness of the system and the story drifts to determine the seismic demand in figures. The results are evaluated and interpreted by taking into account the empirical rules given in the Turkish Seismic Code. It is found that the results of the nonlinear static and dynamic analyses give much more useful information regarding the irregularity than the linear analysis. Therefore the decision on the acceptance of the column discontinuity or on an empirical rule to deal with the column discontinuity should be based on a nonlinear analysis. The nonlinear analysis can be used to specify practical limit for irregularity and to define more precisely regular and irregular structural systems. Furthermore, it can be employed to determine acceptable degree of irregularity.

Keywords: Seismic response, structural irregularities, discontinuities in columns.

1. IRREGULARITIES IN STRUCTURAL SYSTEMS

Often structural systems are designed having various level irregularities in accordance with architectural requirements in order to produce aesthetic buildings. Irregular structures come into being due to discontinuity in mass, stiffness and strength in elevation and due to asymmetric geometrical configuration on plane. Generally, irregularities are classified as planar and vertical in the seismic codes. On the other hand, seismic codes discourage all type of discontinues, because seismic behavior of structural system and seismic demand on structural systems having irregular configuration or asymmetrical distribution of structural elements generally are larger than those of the regular ones. Furthermore, irregularities produce uncertainties in the analysis of the structural system, in the degrees of redundancy and on the load paths. Seismic codes state measures to compensate for uncertainties ranging from a simple requirement of use of modal superposition in case of torsional irregularity and use of a special load combination of gravity and seismic forces in case of out-of-plane offset irregularity. These measures can be recognized as penalties to discourage the irregular structures. However, the imposing of the modal superposition in the seismic design instead of the equivalent static load analysis cannot be recognized as a penalty in the widespread use of the computer software. On the other hand in some cases seismic codes provide empirical rules for dealing with additional seismic demands required due to structural irregularity. Generally these empirical rules require an increase in the structural capacity of the elements which produces the irregularity and those of the structural elements in its neighborhood. Although the seismic codes define irregularities in detail, there is often no definition for the degree of irregularity of the overall three-dimensional system. Often no attempt is made to define level of irregularity in quantifiable manner, for example a parameter ranging from 0 to 1.

Vertical irregularities affect structural response and induce loads that are significantly different from the distribution obtained in the linear analysis by employing regular assumptions. Seismic response of buildings which has vertical irregularity due to column discontinuities studied in numerous studies. In fact the requirements of the seismic codes regarding the irregularities often are reflections of some of the results of the studies. However, most of the studies have focused on the elastic response of the structural system only, whereas limited number of investigation can be found dealing with the nonlinear analysis. Within these framework, various studies can be found where seismic responses of the vertically irregular buildings are investigated and the results are given comparatively, the papers of Aranda (1984), Esteva (1992), Das et al. (2003) and Chintanapakdee et al (2004) are the most notable and recent ones. Fragiadakis et al. (2006) investigated the response of structures with single-story vertical irregularities in stiffness and strength by using a nonlinear dynamic analysis where several acceleration records having various levels of intensity. Güler et al. (1996 and 2004) presented a detailed study on the column discontinuity and documented that various seismic damages came into being due the structural irregularity in the recent Turkish earthquakes. Soni et al. (2006) summarized the studies dealing with the seismic response of frames having vertical irregularity in detail.

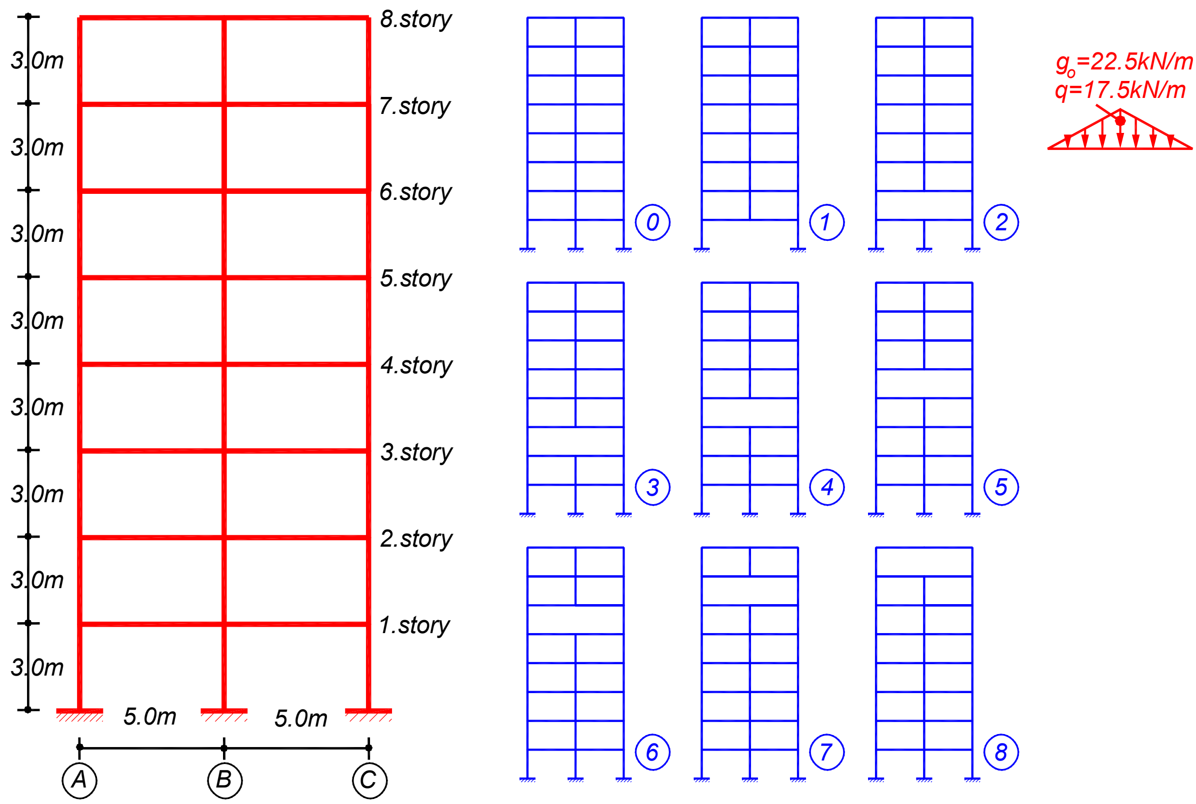

Figure 1. Model frame and models having column discontinuity

2. DISCONTINUITIES IN COLUMNS

Irregularity in structural are defined in plan and in elevation. One of the irregularities in elevation is discontinuity in columns and shear walls. Turkish Seismic Code does not permit columns at any storey to be supported by a cantilever beam. In this way an asymmetrical configuration and loading are avoided at the outer edge of structural system. When the cantilever beam which supports the column has continuity into the structural system, the negative effect of the column discontinuity can be avoided partially. However, this is not permitted in the Turkish Seismic Code as well. Discontinuities in shear walls are not permitted due to large bending moment and shear force to be transferred to the lower stories by means of the supporting beam. On the other hand shear walls supported by the columns are not permitted as well. Here, the continuity of the edge zones of the shear walls can be established by the columns in vertical load. However, the shear walls produce a stiff story, whereas the columns below it cause a soft story, which should be avoided in the seismic loading. Furthermore, this type of structural configuration can produce weak and/or soft story which may cause the total collapse of the building.

Turkish Seismic Code allows only the case where a column which rests on a beam supported at both ends. However, the code requires an increase of 50 % in all internal forces and moments at all sections of the beam and at sections of the other beams and columns adjoining to the supporting beam. This empirical rule is expected to deal with the additional seismic demands. In the present paper the additional seismic demand in the structural system due to discontinuity in columns is studied by considering a frame which has this type of structural irregularity by considering the linear analysis, the pushover analysis and the time history analysis. The results of the numerical analyses are presented in figures and discussed comparatively.

3. FRAME HAVING DISCONTINUOUS COLUMNS

Figure 1 shows a planar frame having eight stories and two spans. All column sections are assumed to be 0.45m×0.45m and the beams to be 0.30m/0.60m in order to decease the parameters of the analysis, so that the numerical results can be interpreted easily. Only the beams which support the discontinuous column have a cross section of 0.40m/0.80m in order to support the load of the column which is not transferred to the column below due the vertical discontinuity. In order to study the column discontinuity, eight frames produced from the main frame are considered. At each frame column discontinuity is assumed to be at a specific story, as Figure 1 shows. The beams are assumed to be loaded by a triangular load gravity load of 22.5kN/m in addition to self weight and a live load of 15.5kN/m. The design of the columns and the beams are done by following the Turkish Design Code for Concrete Structures which has similar requirement as ACI318. The seismic design is accomplished by following the requirements of the Turkish Seismic Code by adopting a seismic load reduction factor of 8. Although the geometry of the beams show almost no variation (except the beam which support the discontinuous column), all beams have different reinforcement obtained from the linear design analysis as explained above, whereas the columns have a minimum reinforcement ratio of 0.01. Linear and nonlinear analyses are carried out to study the effect of the column discontinuity on the behavior of each frame subjected to the vertical and the seismic loads.

The structural behavior of the frame under the factored loads is numerically evaluated and the load path to the support is studied by considering the irregularity due to column discontinuity. Figure 2 shows the variation of the axial force in the side and the middle columns along the height of the system for each frame under the factored gravity and live load (1.4G+1.6Q). As it is seen, the axial force in the side columns increases rapidly above the story where the discontinuity is present, because the middle column do not support the beams properly, due to the column discontinuity. When the middle column appears and transfers the normal force to the columns in the lower stories, then the increase of the normal force becomes less in the side columns. In other words, the discontinuity of the middle column affects the side column by increasing its normal force significantly. Figure 2 shows the axial force variation in the middle column along the elevation of the frame. The force vanishes, when the discontinuity takes place, as expected. When no discontinuity not present, a gradual increase of the normal force takes place downwards. The columns above the discontinuity level support significantly less normal force, due to the elastic vertical displacement at the supports, although the bending rigidity of the beam which support that column is increased significantly. The discontinuity of the column affects the load distribution considerably, where the column can be assumed to have an elastic support. The increase of the bending rigidity and the bending capacity of the column does not seem be effective to produce a relatively rigid support for the column above the discontinuity. This fact shows that the axial stiffness of the columns is significantly larger than the bending stiffness of the beams and comparable beam stiffness can not be obtained by increasing the height and the width of the beam within the acceptable limits. This fact will appears much more pronounced, when the cracked stiffnesses of the beam and the column is employed, because the ratio of the cracked and uncracked stiffnesses of the beam section is around 0.40 and it is around 0.80 for the columns depending on the level of the axial stress. Since the analyses are linear, only the stiffnesses of the beams and the columns is effective in the preceding results, whereas in the nonlinear analysis presented below the reinforcements of the sections are used. In other words, the reinforcements of the cross sections or the bending moment capacity of the sections are not employed in the evaluation of the results presented in Figure 2.

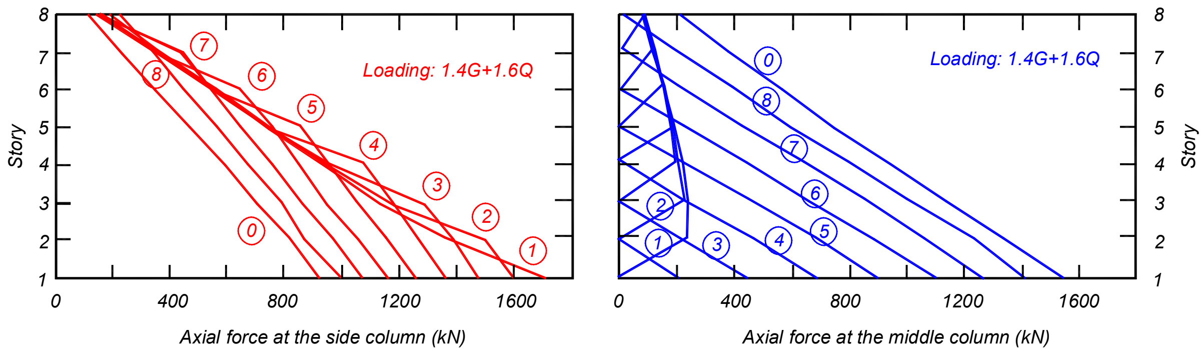

Figure 2. Variation of the axial force in the side columns and in the middle column along the height of the frame

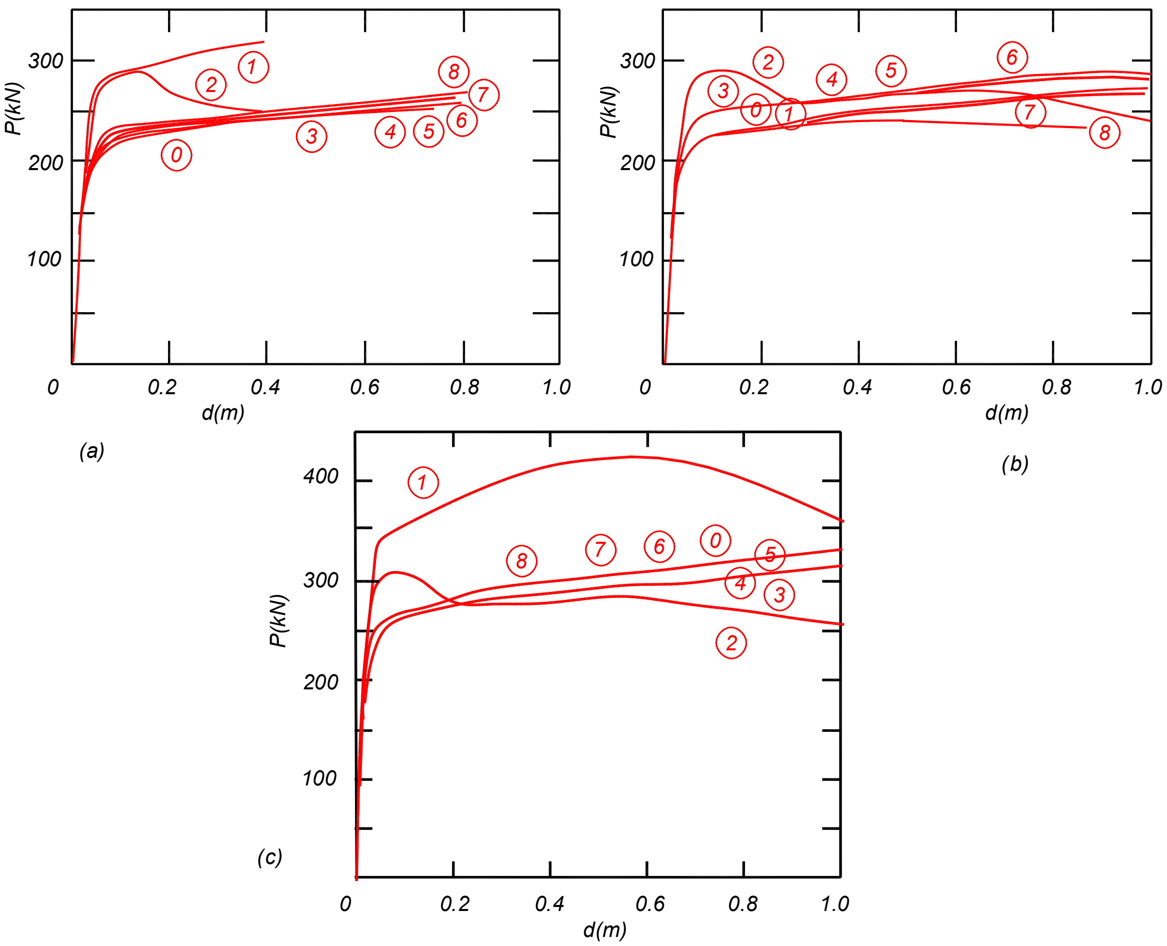

Figure 3. Pushover curves of the frames having column discontinuities, a) external load having the first modal variation, b) external load having the first modal variation with P-Δ effect and c) external load having a constant lateral force variation

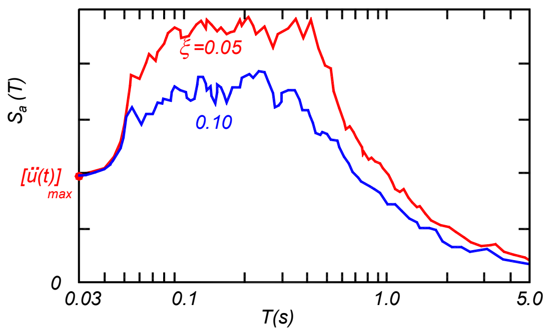

Figure 4. Spectrum of the acceleration record considered in the time history analysis

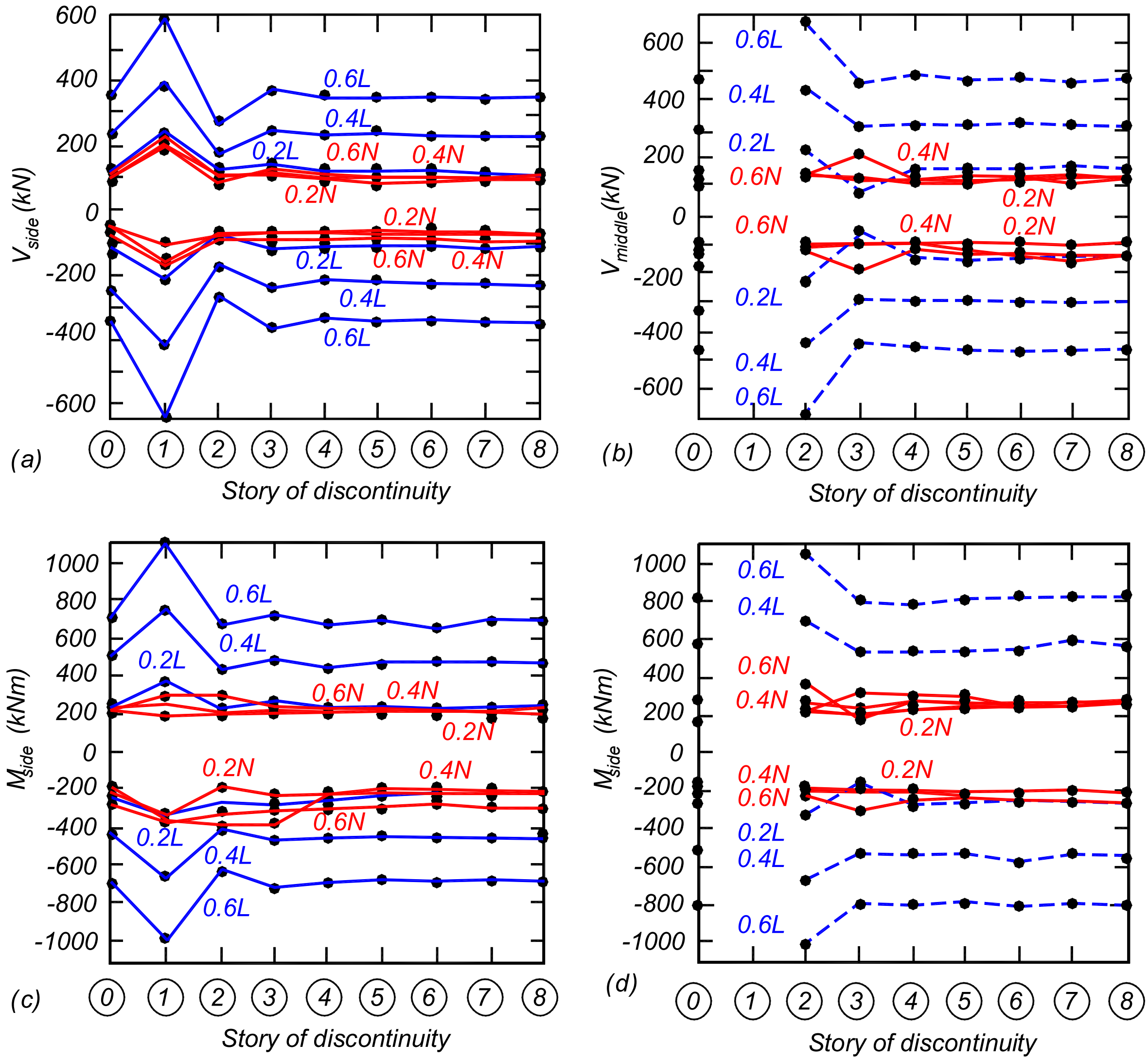

Figure 5. Shear force and bending moment of the side and middle columns of the first story obtained in the time history analysis for the frames having column discontinuity (L: Linear analysis; N: Nonlinear analysis, 0.2, 0,4, 0.6 and 0.8 corresponds to the maximum relative acceleration of the seismic record $[\ddot{u}(t)]_{\max} / g$)

The structural behavior of the frame under the seismic load is numerically evaluated by considering the pushover analysis. In these analyses in addition to the geometry and the reinforcement details of the column and the beam sections are required. The frames are designed by considering the factored and earthquake loadings, i.e., 1.4G+1.6Q and G+Q+E. Although the geometry of the sections is the same, except the beam which supports the discontinuous column, the reinforcements of the beams display a variation. It means that the capacity of the side columns of the frame (1) at the first story is larger than that of the side columns of the frame (0), because the frame (1) has only two columns in the first story due to the column discontinuity. Figure 3 shows the lateral load versus the top displacement curves for various column discontinuity cases, as defined in Figure 1. In Figure 3a the load lateral load assumed to be proportional to the first modal displacement configuration, which is known as the regular pushover analysis. In Figure 3b, the pushover curve is obtained by including the P-Δ effect. The variations in Figure 3c are represent the results where the variation of the lateral load assumed to constant along the height of the frame. As it is seen the maximum lateral load capacity of the frame (1) is larger than of the frame (0) which has no column discontinuity. However, the ductility capacity of the frame (0) much larger than that of the frame (1), as it is shown in the pushover curve given in Figure 3a. Figure 3c shows that the lateral load capacity of the frame increases, when the variation of the lateral load is constant due to the positive effect of the loading. Often constant lateral load variation is considered to include the higher mode contributions to that of the first mode, which becomes effective for the high of the building is large.

The maximum shear force and bending moment of the side and the middle columns obtained in the time history analysis to evaluate the dynamic behavior of the frame having column discontinuity. Figure 4 shows the spectrum of the acceleration record employed in the numerical analysis for two damping ratios. As is expected the spectrum curve starts from the maximum value of the acceleration record, i.e., $[\ddot{u}(t)]_{\max}$ and reaches to $2.5[\ddot{u}(t)]_{\max}$ approximately for $T = 0.1s$. The curve displays this maximum value for $0.1s \leq T \leq 0.4s$ and decreases asymptotically for increasing periods. Although the shape of the spectra does not change, the maximum of the acceleration record is varied in between $0.2g$ and $0.6g$. Figure 5 shows the maximum shear force and bending moment of the side and the middle columns of the first story obtained in the time history analysis for the frames having column discontinuity. The analysis is carried out by employing the linear and nonlinear analyses. The curves indicates that $0.4L$ corresponds to the results obtained by employing the linear analysis using the acceleration record having the maximum of $0.4g$. The results of the nonlinear analysis are denoted as N . The maximum values of the shear and the bending moment are determined by the capacity of the cross section. The small variation in the bending moments comes into being due to the variation in the axial force in course of the time history analysis. However, in the linear analysis the shear force and the bending moment increase for the larger accelerations, as expected. Especially the increase becomes pronounced, when a column discontinuity is present. When the column discontinuity is in the upper stories, the shear force and the bending moment at the first story become less effective. Story drift demands of the frames are obtained in the time history analysis are shown in Figure 6. The linear and the non linear analysis are carried out by employing a seismic record having a spectrum given in Figure 4. However, the relative maximum acceleration of the seismic record $[\ddot{u}(t)]_{\max} / g$ is assumed to be 0.2, 0.4 and 0.6. As the figure shows the maximum story drift increases as the maximum of the record gets larger. The position of the discontinuity has also a pronounced effect on the inelastic story drift. The discontinuity at the lower stories increases the story drift substantially.

4. CONCLUSIONS

Column discontinuity alters the load path in the structural system. Seismic codes classify, discourage irregularity and require increases of in all internal forces by employing a empirical rule to deal with the additional seismic demands. From the above numerical results and explanation the following conclusion can be stated:

a. The nonlinear behavior of the frame having column discontinuity quite different that the linear behavior. It is regularly difficult to predict the nonlinear behavior of the frame having column discontinuity by evaluating the linear analysis. Furthermore, the nonlinear story drift demand is significantly large, when the column discontinuity is in the lower stories of the frame. High ductility demands in the neighborhood of the story of the irregularity are observed.

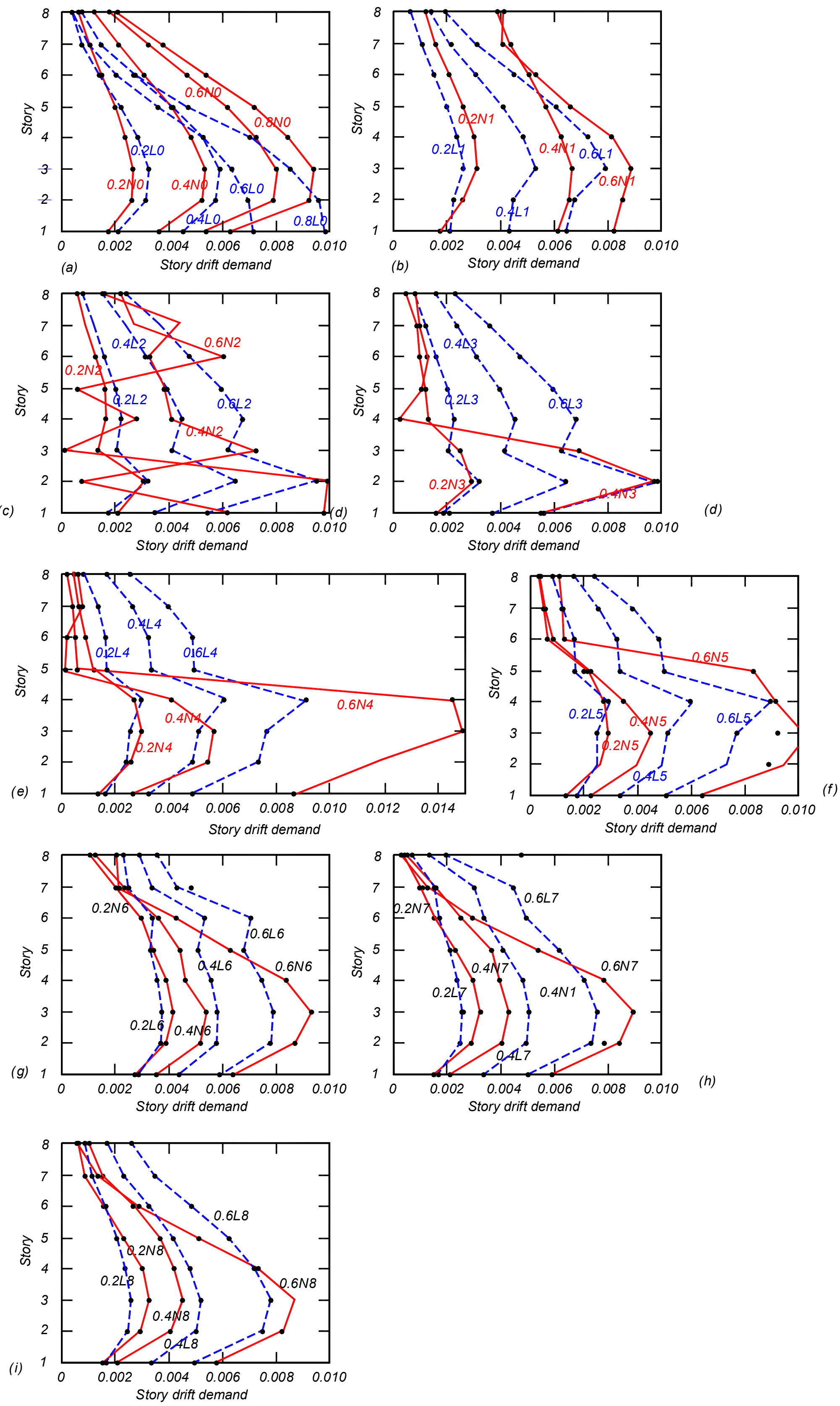

Figure 6. Story drift demand of the frames obtained in the time history analysis for the frames having column discontinuity (L : Linear analysis; N: Nonlinear analysis, 0,1,2,3,4,5,6,7,8 corresponds to the story number where discontinuity is present and 0.2, 0,4, 0.6 and 0.8 corresponds to the relative maximum acceleration of the seismic record $[\ddot{u}(t)]_{\max} / g$)

b. Design codes classify irregularity and require increases of in all internal forces. However, due to column discontinuity the load path changes in the structural system considerably and the empirical requirements given in the codes are expected to deal with the additional seismic demands do not seem to be satisfactory. Furthermore, the effect of the discontinuity is more much pronounce, when the frame has only two spans, as it is the case in the present analysis. Column discontinuity produces the soft story in the frame, when the number of the column is small in a specific story.

c. There are large numbers of parameters which affect the behavior of the frame subjected to vertical and lateral loads. The variation of the load path depends on the stiffness distribution in the columns and beams neighboring the column discontinuity. Especially, the decrease in the stiffness of the beam which supports the discontinuous column affects significantly the load path to the support of the structural system. Remembering that the cracking of the concrete section decreases the bending stiffness up to %30, the significance of the variation can be understood.

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