Performance Based Design of Reinforced Concrete Open Ground Storey Buildings

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ABSTRACT

Open ground storey (OGS) buildings are buildings on stilt floors which provide for vehicle parking space in the ground floor. Such buildings where the mass and stiffness is not uniform are called irregular buildings and are known to perform poorly under seismic loading. As a result the Indian code for evaluating earthquake loads on buildings penalizes these buildings by requiring their ground storey to be designed for two-and-a-half times the estimated base shear for a similar non-open ground storey building with no conditions on required stiffness. However, this may lead to undesirable performance because the ground storey columns are likely to get heavily reinforced and as a consequence have reduced levels of ductility. Also, since most of the lateral deformation of the building is likely to be concentrated at the ground storey, the storey drift is likely to exceed the stipulated values even under minor or moderate earthquakes thus causing performance problems. In this study, the performance of 26 two-storeyed and 58 four-storied OGS plane frames, designed and detailed as per the Indian Codes, is evaluated by non-linear static pushover analysis. The frames were designed and analyzed by varying the parameters such as the number of storeys, the ground floor to upper floor stiffness ratio, the percentage of reinforcement in the columns and the intensity of ground motion. The beams and columns were modeled by frame elements with appropriate moment and shear hinge properties. The infill walls were modeled by equivalent truss elements for which appropriate axial hinge properties were given. The response is characterized by Inter-storey drift index and ductility demands. Based on the results of pushover analysis, it was observed that inter-storey drift as well as ductility demand increased with increase in intensity of ground motion, increase in percentage of reinforcement and is independent of the stiffness ratio. The relationships obtained between the response parameters with system parameters can be used to achieve the desired performance of such buildings.

Keywords: *Reinforced concrete (RC), Open ground storey (OGS), Performance based design (PBD), pushover analysis*

1 INTRODUCTION

Seismic design codes are traditionally based on the force-based approach wherein structures are designed with a certain minimum lateral strength. However, it has been observed that such an approach which relates to the elastic response does not produce consistent inelastic response in terms of the amount and distribution of damage in structural elements. In view of the above, the displacement based approach also known as performance based design approach has been explored in recent years and found to give better results. In this approach, the prime response quantities of interest are the inter-storey drifts and the design process directly attempts to limit these drifts to an acceptable value. However, for adopting this method, one has to understand the influence of various design parameters such as the strength, stiffness and detailing aspects like the percentage of reinforcement on the response parameters like inter-storey drift. A study to understand the influence of the design parameters on the response parameters was undertaken for reinforced concrete regular plane frames and the results were presented in Kumar and Venkateswarlu (2008). The suitability of non-linear static pushover analysis in predicting the seismic response was also ascertained. In this study, the method is used to understand the response of Open-ground Storey (OGS) Buildings.

Reinforced Concrete (RC) moment resisting frames are popular compared to structural steel frames in developing countries like India, due to low cost of material and labour. The frames bounded by RC beams and columns are filled by masonry wall panels to divide spaces according to functional requirements and also to protect the inside of the structure from vagaries of weather like rain, wind and snow. In general practice, infill panels used in the RC framed buildings are assumed to be non-structural elements and their strengths and stiffness's are neglected in the analysis and design of structures, while their masses are taken into consideration for load calculations. However, infill walls alter the behaviour of the building from predominant frame action to predominant truss action and carry the lateral seismic force along their diagonals (Murthy and Jain 2000). When infill walls are not evenly distributed in elevation, it causes vertical irregularity such as the soft storey effect. A special and a very common class of soft storey buildings are those with parking facilities in the ground floor and they are called as open ground storey (OGS) buildings. Such buildings have mainly three types of vertical irregularities namely mass, strength and stiffness irregularity.

OGS buildings are relatively flexible in the ground storey i.e. the relative horizontal displacement in the ground storey is much larger than in the upper stories. Such buildings are also relatively weak in the ground storey i.e. the total horizontal earthquake force that can be carried in the ground storey is significantly smaller than the horizontal load carrying capacity of the upper stories. Thus the open ground storey is both a soft and a weak storey. The infill walls present in the upper storeys of the OGS buildings increases the stiffness of the building globally. Due to the increase in global stiffness, the base shear demand on the building also increases. In the case of completely infilled frame building, the increased base shear is shared by both frames and infill walls in all the storeys. In OGS buildings, where the infill walls are not present in the ground storey (no truss action), the increased base shear is resisted entirely by the ground storey columns. The increased shear forces in the ground storey columns will induce increased bending moments thereby causing higher curvatures and relatively larger drifts at the first floor level. The large lateral deflections further enhance the bending moments due to the P-Δ effect. Plastic hinges develop at the top and bottom ends of the ground storey columns. The upper storeys would remain undamaged and move almost like a rigid body and the damage is mostly concentrated in the ground storey columns, and this is termed as a 'soft-storey collapse'.

In this study, the performance of 26 two-storied and 58 four-storied OGS plane frames, designed and detailed as per the Indian Codes, is evaluated by non-linear static pushover analysis. The frames were designed and analyzed by varying the parameters such as the number of storeys, the ground floor to upper floor stiffness ratio (K_{GF}/K_{FF}), the percentage of longitudinal reinforcement (P_t) in the columns and the Intensity of ground motion represented by factor (Z/R) where Z is the zone factor and R is the response reduction factor. The beams and columns were modeled by frame elements with appropriate moment and shear hinge properties. The infill walls were modeled by equivalent truss elements for which appropriate axial hinge properties were given. The response is characterized by ground floor Inter-storey drift index (IDI) and ductility demands. Only the results of IDI are presented in this paper. Based on the results of pushover analysis, it was observed that inter-storey drift as well as ductility demand increased with increase in response reduction factor, increase in percentage of reinforcement and decrease in the stiffness ratio. The relationships obtained between the response parameters with system parameters can be used to achieve the desired performance of such buildings.

2 LITERATURE REVIEW

Tuladhar and Kusunoki (2005) reported that arrangement of infill wall in the frame affects the behaviour of the structure and that a relationship can be established between strength increasing factor (η) and initial stiffness ratio (K_{FF}/K_{GF}). The strength increasing factor (η) can be used to take care of the soft storey effect without carrying out the non-linear analysis. They also found that non-linear dynamic time history analysis for 3D models proved that the demand on the soft ground storey is met by the application of the strength increasing factor (η). The strength increasing factor was found to be almost equal to the initial stiffness ratio implying that the lack of stiffness can be compensated by increased strength.

Ravi (2006) studied the performance of two, four, six and eight-storeyed OGS frames with stiffness ratios ranging from 0.6 to 1.0. It was reported that the ductility factor increased with decrease in the stiffness ratio (K_{GF}/K_{FF}) but concluded that the stiffness ratio has no definite effect on the performance.

Kumar and Venkateswarlu (2008) reported that the percentage of longitudinal reinforcement has considerable effect on the seismic performance and should be considered in performance based design. The relationships obtained between the response parameters namely ductility, drifts and damage indices with system parameters such as time period, response reduction factor and percentage of longitudinal reinforcement can be used to achieve the desired performance of RC frames.

3 MODELLING AND ANALYSIS OF RC FRAMES

Single bay two and four storey RC plane frames located in seismic zones 3, 4 and 5 for varying system parameters like stiffness ratios (K_{GF}/K_{FF}), percentage of longitudinal reinforcement in column (Pt) and ground motion level (Z/R) were designed and analyzed for gravity loads as per IS 456:2000 and lateral loads (earthquake loads) as per IS 1893(part-1):2002 for the maximum considered earthquake (MCE) and detailed as per IS 13920:1993. The basic data pertaining to the four-storied frames is given in Table 1. The modelling of the frames was carried out using SAP 2000NL v 11. The numerical model represents all components that affect the strength, stiffness and the mass of the frame elements, infill walls (truss element). Non-linear static pushover analysis was carried out to get the response of the RC plane frames and the analysis results are compared to evaluate the performance of the frames. The stiffness ratio (K_{GF}/K_{FF}) was varied after taking into consideration the contribution of infill wall stiffness to the storey stiffness. The variation of response parameters (Inter storey drift index and local damage index) with the system parameters was studied to arrive at the relationship between them. These in turn can be used to propose guidelines to achieve a desired performance of OGS frame building.

For developing the moment versus rotation curve of a hinge, the stress-strain model for concrete subjected to uniaxial compression and confined by transverse reinforcement as proposed by Mander *et al* (1988) and modified by Panagiotakos and Fardis (2001) was used. Beams and Columns were modelled with concentrated plastic hinges at the ends. Beams have both moment (M_3) and shear (V_2) hinges whereas, columns have axial load plus moment (P-M_3) hinges and shear (V_2) hinges. The shear hinge properties of columns were calculated using the model proposed by Sezen (2007). Infill wall struts were assigned axial hinges based on model proposed by Asokan (2006) which is based on the ultimate load method proposed by Saneinejad and Hobbs (1995) (see Fig. 1(b)). The plastic hinge rotation, deformation and moment, shear force values corresponding to yield and ultimate states were calculated for each section and used to define the hinge properties.

4 PARAMETRIC STUDY OF RC FRAMES

In this study, first the stiffness ratio (K_{GF}/K_{FF}) is satisfied by assigning the dimensions for frame elements and struts and thereafter the static analysis is carried out and the design moments, shear forces, axial forces are determined for the governing load combination so as to satisfy the desired percentage range of longitudinal reinforcement in columns (p_t) criteria. Nonlinear static pushover analysis was carried out only for those cases where both the criterion were satisfied. The nomenclature of the different OGS RC plane frames is $nSZ_nK_nR_nP_{tn}$, where,

nS = number of storey's i.e. 2S and 4S

Z_n = seismic zone i.e. Z_1=Seismic zone 3, Z_2=Seismic zone 4, Z_3=Seismic zone 5

K_n = stiffness ratio (K_{GF}/K_{FF}) i.e. K_1 =0.8, K_2 =1.0, K_3 =1.2

R_n = response reduction factor i.e. R_1 =3, R_2 =5, R_3 =7
P_{tn} = percentage range of longitudinal reinforcement in columns i.e. P_{t1}=1.0% - 1.5%, P_{t2}=1.5% - 2.0%, P_{t3}=2.0% - 2.5%.

The design parameters considered are limited to stiffness, strength and percentage of reinforcement while the response parameters considered are inter-storey drifts index and local ground floor ductility demand. For medium rise buildings of two and four-storeys, the ground floor column sizes is either the same as or one size larger than first-floor column size and the extra strength required is achieved by increasing the percentage of reinforcement. The increase in first storey stiffness due to infill walls partly offsets the increase in ground floor column size. Hence, values of stiffness ratios considered were 0.8, 1.0 and 1.2 as values outside this range are not common. As per the Indian code IS1893 (2002), R values of 3 and 5 only are possible but to better understand the influence of this parameter, R value of 7 was also considered. For parametric study, different values of stiffness ratios (K_{GF}/K_{FF}) (0.8, 1.0 and 1.2), response reduction factor R, (3, 5 and 7) and percentage range of reinforcement in columns (1.0% - 1.5%, 1.5% - 2.0% and 2.0% - 2.5%) for seismic zones 3, 4 and 5 were considered. Each frame was subjected to 2×3×3×3 (2 Seismic zones, 3 Stiffness ratio values, 3 R values, 3 percentages of reinforcement). A total of 26 two-storied and 58 four-storied frames were considered in the study as shown in Table 2 and Table 3 respectively.

In the present study, the inter storey drift index (IDI) is defined as the difference in displacement of two consecutive floors divided by the storey height and is expressed as a percentage. Only the ground floor IDI is reported in this paper.

5 RESULTS AND DISCUSSIONS

The results are presented as variations of the response parameter (IDI) as a function of the system and ground motion parameters. The inter storey drift has a complex dependence on the relative storey stiffnesses as well as the strength of the structural elements. However, to understand the effect of each individual parameter, it is necessary to decouple their dependence. Accordingly, first the variation of the inter-storey drift index (IDI) is plotted against the percentage of reinforcement as shown in Fig. 4(a) and Fig. 5(a) for the two and four-storeyed frames respectively. It can be observed that the IDI increases with increase in percentage of reinforcement although the relationship is not very clear. This is expected as larger reinforcement percentage will be required for smaller column size. The relationship between IDI and pt is expressed as a linear function F_1.

Next, the IDI values were divided by the function $F_1(p_t)$ and the results were plotted against the earthquake intensity factor represented by Z/R as shown in Fig. 4(b) and Fig. 5(b) for the two and four-storeyed frames respectively. The data for each zone is looked at separately and a linear relationship is obtained between IDI and Z/R for each zone. The general trend is that IDI is decreasing with Z/R. This is due to the fact that as the intensity of ground motion increases stronger and consequently stiffer columns are required at the ground level to resist the base shear leading to less storey drifts.

Finally, the IDI is divided by both F_1(Pt) and F_2(Z/R) and the result is plotted against the storey stiffness ratio K. It can be observed that there is considerable variation of this quantity for each value of K. However, interestingly, the values are balanced on either side of unity and a best fit line is almost horizontal at the value of one. Hence it can be concluded that the storey stiffness ratio has no definite effect on the IDI at large inelastic deformations as the infill wall is likely to lose its stiffness and later its strength thereby reducing the degree of irregularity. What is important is that the ground storey columns should be ductile enough to survive large deformations at which the upper storey walls are likely to collapse.

6 CONCLUSIONS

1. Open-ground storey (OGS) frames designed and detailed as per current codal procedures give widely different performance under severe earthquakes. This underscores the need to understand

the influence of various design parameters and revise the design procedure to get better performance.

2. Some design parameters such as ground motion levels and percentage of longitudinal reinforcement have considerable effect on the seismic performance of OGS frames and so must be considered in performance based design. The variation of storey stiffness ratio within the range considered in this study has no specific effect on the ground floor storey drift and so need not be considered in performance based design of OGS frames.

3. The relationships obtained between the response parameter namely inter-storey drift of the ground floor with design parameters such as ground motion level and percentage of longitudinal reinforcement can be used to achieve the desired performance of OGS buildings.

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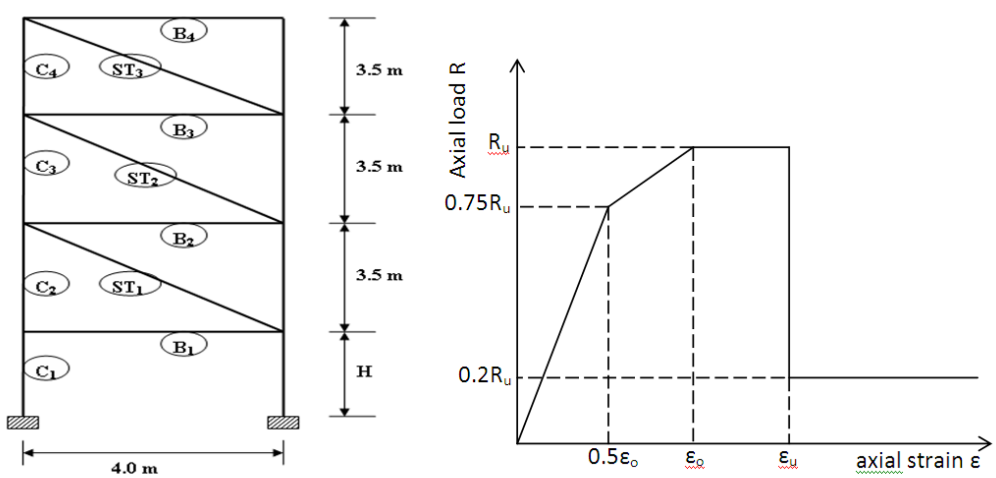

Figure 1 Four-storey frame model with struts representing infill walls and the strut load-strain model

Table 1 Basic data of four-storey OGS RC plane frames

S.No.	Description	Information
1	No. of upper storeys	3
2	Type of Frame	RC Frame with open ground storey
3	Height of Upper/Ground floor	3.5 m
4	Beam Length	4.0 m centre to centre
5	Soil Type/ Support conditions at base	Rocky/ Fixed
6	Beam – Column Joint	Joint Rigidity is taken as 1.0
7	Grade of Concrete/ Steel	M25/ Fe 415
8	Dead Loads (unit weights) Brick masonry/ RC	19.2 kN/m^3/ 25.0 kN/m^3
9	Imposed(Live) Loads	2.5 kN/m^2
10	Minimum Clear Cover Beams/ Columns	30 mm/ 40 mm
11	Type of vertical stirrups used	8 mm (two / three legged)
12	Thickness / width of slab	150 mm/ 1.5 m on either side
13	Thickness of Infill wall Partition/ External wall	110 mm/ 230 mm
14	Importance Factor, I	1.0
15	Seismic Zone	3, 4 and 5
16	Zone Factor, Z	$Z_1 = 0.16$, $Z_2 = 0.24$ and $Z_3 = 0.36$
17	Response Reduction Factor, R	$R_1 = 3.0$, $R_2 = 5.0$ and $R_3 = 7.0$
18	Stiffness Ratio (K_{GF}/K_{FF})	$K_1 = 0.8$, $K_2 = 1.0$ and $K_3 = 1.2$
19	Percentage of Longitudinal reinforcement in column (Pt)	P_{t1} = 1.0 to 1.5%, P_{t2} =1.5 to 2.0% and P_{t3} = 2.0 to 2.5%

Table 2 List of Two-storied frames analyzed and their IDI values

No	Frame	IDI	No	Frame	IDI	No	Frame	IDI
1	2SZ1K1R1Pt2	0.396	11	2SZ2K2R1Pt3	0.432	21	2SZ3K2R3Pt1	0.356
2	2SZ1K1R1Pt3	0.456	12	2SZ2K2R2Pt1	0.356	22	2SZ3K2R3Pt2	0.368
3	2SZ1K1R2Pt1	0.284	13	2SZ2K2R2Pt2	0.32	23	2SZ3K3R2Pt2	0.356
4	2SZ1K2R1Pt1	0.312	14	2SZ2K2R3Pt1	0.232	24	2SZ3K3R2Pt3	0.316
5	2SZ1K2R1Pt2	0.320	15	2SZ2K3R1Pt2	0.392	25	2SZ3K3R3Pt1	0.296
6	2SZ1K3R1Pt1	0.280	16	2SZ2K3R1Pt3	0.328	26	2SZ3K3R3Pt2	0.432
7	2SZ1K3R1Pt2	0.316	17	2SZ2K3R2Pt1	0.32			
8	2SZ2K1R2Pt2	0.336	18	2SZ3K1R3Pt2	0.336			
9	2SZ2K1R2Pt3	0.424	19	2SZ3K1R3Pt3	0.424			
10	2SZ2K1R3Pt1	0.248	20	2SZ3K2R2Pt3	0.432			

Table 3 List of four-storied frames analyzed and their IDI values

No	Frame	IDI	No	Frame	IDI	No	Frame	IDI
1	4SZ1K1R1Pt1	0.123	21	4SZ2K2R1Pt1	0.157	41	4SZ3K2R1Pt1	0.143
2	4SZ1K1R1Pt2	0.203	22	4SZ2K2R1Pt2	0.189	42	4SZ3K2R1Pt2	0.149
3	4SZ1K1R1Pt3	0.283	23	4SZ2K2R1Pt3	0.200	43	4SZ3K2R1Pt3	0.166
4	4SZ1K1R2Pt1	0.177	24	4SZ2K2R2Pt1	0.160	44	4SZ3K2R2Pt1	0.160
5	4SZ1K1R2Pt2	0.266	25	4SZ2K2R2Pt2	0.209	45	4SZ3K2R2Pt2	0.163
6	4SZ1K2R1Pt1	0.120	26	4SZ2K2R2Pt3	0.311	46	4SZ3K2R2Pt3	0.206
7	4SZ1K2R1Pt2	0.174	27	4SZ2K2R3Pt1	0.203	47	4SZ3K2R3Pt1	0.194
8	4SZ1K2R1Pt3	0.269	28	4SZ2K3R1Pt1	0.157	48	4SZ3K2R3Pt2	0.206
9	4SZ1K2R2Pt1	0.174	29	4SZ2K3R1Pt2	0.189	49	4SZ3K2R3Pt3	0.300
10	4SZ1K3R1Pt1	0.111	30	4SZ2K3R1Pt3	0.200	50	4SZ3K3R1Pt1	0.137
11	4SZ1K3R1Pt2	0.174	31	4SZ2K3R2Pt1	0.160	51	4SZ3K3R1Pt2	0.149
12	4SZ1K3R1Pt3	0.260	32	4SZ2K3R2Pt2	0.200	52	4SZ3K3R1Pt3	0.166
13	4SZ1K3R2Pt1	0.174	33	4SZ2K3R2Pt3	0.234	53	4SZ3K3R2Pt1	0.140
14	4SZ2K1R1Pt2	0.189	34	4SZ2K3R3Pt1	0.186	54	4SZ3K3R2Pt2	0.163
15	4SZ2K1R1Pt3	0.200	35	4SZ3K1R2Pt1	0.160	55	4SZ3K3R2Pt3	0.206
16	4SZ2K1R2Pt1	0.166	36	4SZ3K1R2Pt2	0.163	56	4SZ3K3R3Pt1	0.143
17	4SZ2K1R2Pt2	0.209	37	4SZ3K1R2Pt3	0.206	57	4SZ3K3R3Pt2	0.206
18	4SZ2K1R2Pt3	0.314	38	4SZ3K1R3Pt1	0.194	58	4SZ3K3R3Pt3	0.269
19	4SZ2K1R3Pt1	0.214	39	4SZ3K1R3Pt2	0.206			
20	4SZ2K1R3Pt2	0.263	40	4SZ3K1R3Pt3	0.300			

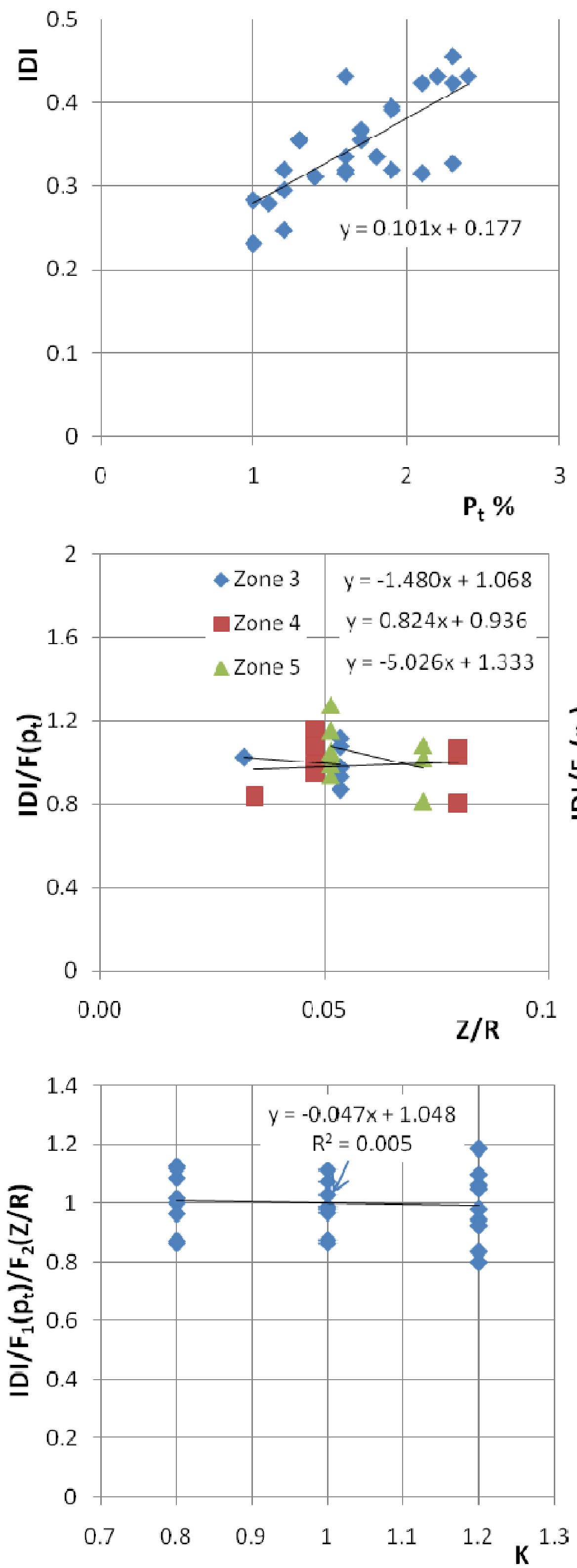

Figure 2 Variation of IDI with percentage of reinforcement (pt), ground motion level (Z/R) and stiffness ratio K for two-storeyed frames.

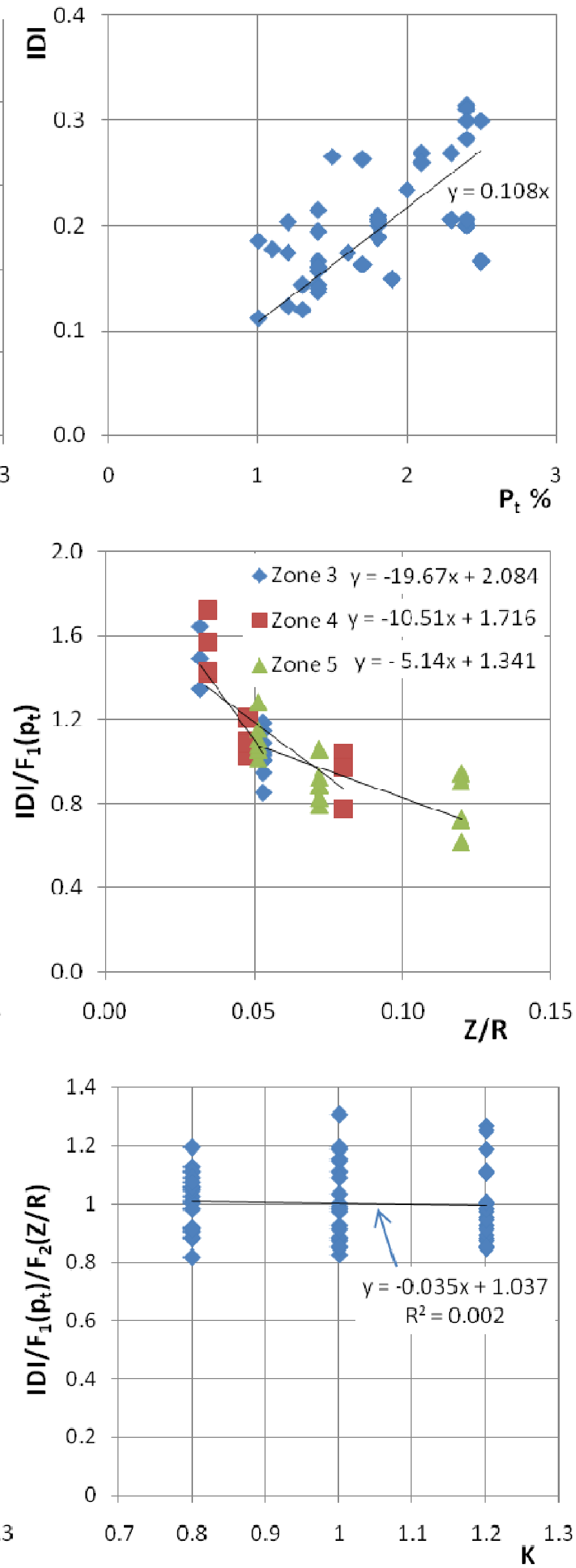

Figure 3 Variation of IDI with percentage of reinforcement (pt), ground motion level (Z/R) and stiffness ratio K for four-storeyed frames.