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Study of inter story drift demands of multi-story frames with RBS connection

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Abstract

RBS connections are one of the most common deformable connections in the world. The plastic hinge will be placed in a conducted mode at a specific area in the beam using this type of connection. It is worth to mention that reducing the sectional area of the beam flange, in general, will cause a reduction in the strength and lateral stiffness of the structure. Hence, the effect of fabrication of the RBS connection, on the frame stiffness and lateral displacement of steel bending frames is analyzed. Regarding the high effect of drift on building's damages, the effect of fabrication of RBS connections on increasing or decreasing of the frame drift are analyzed. In order to investigate the effect of fabrication of RBS connections, the results of RBS connection are compared with the results of cover plate connection.

Keywords: Steel rigid connection; RBS connection; Cover plate connection; Drift; Time History.

1. Introduction

After Northridge earthquake, most researches were directed toward making bending connections in steel structures more ductile. One of the different kinds of these connections is RBS (reduced beam section connection). In this kind of connection, reducing flange section near the end of the beam and within a definite length makes the plastic hinge move to the reduced part and expanding plastic hinge in the length of cut area causes a significant ductility in the hinge. In fact, reduced flange section acts like a fuse and prevents the initial cracks in the connection (FEMA 355D 2000). The most common kinds of RBS connections are: (i) RBS with straight reduced section (ii) RBS with tapered cut reduced section (iii) RBS with radius reduced section (FEMA 350 2000). Other researchers (Pan et al. 2007) investigated optimal flange shape under monotonic loads. The optimal shape strongly depends on the upper bound of the equivalent plastic strain, which is to be specified in practice based on the performance required for each frame (M. Ohsaki et al. 2009), and other new type of Reduced Beam Section (RBS) connection, ``Accordion Web RBS (AW-RBS)'' were used (Seyed Rasoul Mirghaderi et al. 2010 & G.S. Prinz et al. 2009 & Amir A. Hedayat et al. 2009). The AW-RBS decreases the web contribution in moment strength and a reduced section is developed in the beam (Seyed Rasoul Mirghaderi et al. 2010), so it can't be used regularly and in wide range in construction of buildings. Most researches approve using different kinds of RBS connections (FEMA 355D 2000 & Chad S. Gilton 2002). Most of the experiments which are carried out include the sizes of the beams and the kinds of the steels used in practice. The primary studies on this kind of connection indicate that this connection has got some appropriate unique characteristics such as high ductility, appropriate resistance, less cost in comparison to other bending connections, much less operation time for building and installing structure, much more assurance to the welding and it's welding at work place. In this kind of connection by cutting some parts of the flange, the plastic hinge moves by the side of the column into the area within the beam, and as a result there won't be beam-column connection problems at the work place anymore. The reduced area absorbs much more energy by its plastic function and makes a controlled hinge with a wonderful ductility (FEMA 355D 2000).

In multi-story bending steel frames, it is favourable if a regular frame is designed so that the plastic hinge can be made in the beams and the columns remain elastic (the weak beam - strong column rule). Using reduced beam section in the width of flange in the vicinity of beam-column joint is a good design for improving ductility effect in frames which are exposed to intense earthquake loading. The reduced beam section reduces the force directed to the parts of the beam-column joint by directing and regulating stress properly, besides it reduces the volume of welding metal and increases the stiffness of the connection (FEMA 355D 2000&Sac 2000). One of the most remarkable characteristics of RBS connections with radius cut is the strain hardening. According to K.V Grubbs's investigations, for a 50 percent reduction in section, the reduction in stiffness is about 6 to 7 percent and for a 40 percent reduction in flange section this amount falls to 4 to 5 percent (Grubbs K.V 1997). But the reduction of stiffness also causes a rise in the lateral drift of the story. Regarding the fact that drifting is considered as one of the important criteria in designing steel structures, so it seems research worthy to investigate the effect of RBS connection on drift. In this study, the effect of this connection on the drift of the structure is investigated. Nonlinear time history analysis is used for investigating the effect of RBS connection on the amount of the inside drifting angle of the story.

Shen et al. (2000) Kitjasateanphun et al. (2001) and Jin and El-Tawil (2005) conducted analytical studies on the seismic performance of steel moment-resisting frames including RBS connections. The results confirmed that RBS frames can economically provide proper seismic performance in regions of high seismic risk (Seyed Rasoul Mirghaderi et al. 2010).

2. The Effect of Making RBS Connection on the Seismic Behaviour of the Structure

In order to investigate the effect of making RBS connection on the seismic behaviour of the structures numerous frames which had both RBS connection and top and bottom flange cover plate Connection were analyzed. First frames were designed by means of AISC-ASD code and weak beam-strong column rule was also considered (FEMA 355D 2000&AISC 2005). And then the effect of RBS connection on steel moment frames was investigated by means of dynamic nonlinear time history analysis.

2.1 Inputs for Time-History Analysis

In general, two different criteria for record selection can be employed (A.Y. Elghazouli et al. 2008). One consists of choosing the records according to strong-motion parameters and the other is based on geophysical criteria (A.Y. Elghazouli et al. 2008). The search based on strong-motion parameters consists of finding records that have similar shape to the response spectrum provided by the code, obtained for a site with similar characteristics. An efficient procedure may consist, for example, of calculating the average root-mean-square deviation (Drms) of the spectrum of the tentative record from the target design spectrum (A.Y. Elghazouli et al. 2008). Alternatively, spectrum compatible artificial records may be generated from white noise. This latter technique however tends to create unrealistic records both in terms of frequency, phase content, number of cycles and duration of motion (A.Y. Elghazouli et al. 2008 & Bommer JJ et al. 2004). On the other hand, for situations where the site is well characterized in seismological terms by either a deterministic or probabilistic seismic hazard assessment, then one or more earthquake scenarios can be established. Accordingly, the fault mechanisms and the ranges of magnitudes and fault distances of the earthquakes affecting the site are known (A.Y. Elghazouli et al. 2008 & Bommer JJ et al. 2000). In this case, the selection can be conducted by searching a strong-motion database for records that match those geophysical parameters. The selection of records is carried out herein by combining the two criteria discussed above. The records are selected by imposing the following conditions: (i) moment magnitudes (Mw) larger than 6 since Spectrum Type 1 corresponds to high magnitude events (A.Y. Elghazouli et al. 2008 & Rey J et al. 2002); (ii) records involving near-fault or forward directivity effects are avoided; (iii) rock or stiff soil sites, for consistency with the soil type assumed in design; (iv) PGA larger than 0.03g, to avoid applying unrealistically high scaling factors. The duration was not specifically considered since the model structures do not exhibit significant degradation effects. Records with forward directivity effects were not considered although it should be noted that they can pose a high damage potential to flexible structures (Alavi B et al. 2004). Concerning the given explanations, the earthquake records of Manjil, Tabas and Elentero are used. 20 sec time period for Tabas and Elentero and 15 sec time period for Manjil earthquakes are used. Then the maximum acceleration of each earthquake spectrum is levelled up to 1g in the related interval (PGA). After levelling earthquake records (up to 1g) the response spectrum is computed for earthquake records. By calculating the average root-mean-square deviation (Drms) of the three spectra, the mean response spectrum derives. After this stage, the mean spectrum is compared with standard design spectrum. This comparison like proposed relations is to be between 1.5T to 0.2T limits (T, period of structure). For instance, for a 10-story model which has 1.15 sec period, scaling is done between 0.23 and 1.72. The scaling coefficient for 10-story structure equals to 0.87 in period of 1.72. So, these three spectra for dynamic linear time history analysis are utilized. Under such conditions all three spectra have the same maximum acceleration equals 0.87g. Of course, it never means that the derived response is the same for the all three spectra. Because the frequency content of the spectra is different, the amount of force directed to the structure will also be different. As it can be observed, three different spectra with three different frequency contents are used in the analysis.

2.2 RBS Connection Designing Process

For designing RBS connection with radius cut, FEMA proposed equations are used (1, 2, 3). a, b, c and R respectively stand for the distance from the cut zone to the column, the length of the cut, maximum amount of cut, and radius cut (figure 1). Also Bf and d stand for the width of the flange and the reduced beam section respectively (Engelhardt M. D et al. 1998).

$$a = (0.5 \approx 0.75)b_f \quad (1)$$

$$b = (0.65 \approx 0.85)d \quad (2)$$

$$c = (0.2b_f \approx 0.25b_f) \quad (3)$$

$$R = \frac{4c^2 + b^2}{8c} \quad (4)$$

2.3 Modeling the Frames under Investigation

For modeling, first samples were analyzed by the ETABs software and designed by AISC code (AISC 2005). Two dimensional frames were used for modeling, and models were design so that they cover various bays and numerous stories. The SAP2000 software is used for dynamic non-linear analysis. The modeling process of frame's plastic behavior in this software is based on plastic hinge theory. Also, Newmark method for dynamic non-linear analysis is used. For investigating the results of frames with RBS connection, one of the most common kinds of connections in Iran, that is, Cover Plate Connection is compared. In order to name frames concerning the kind of connections two methods are followed. For frames with RBS connection and flange cover plate connection, RBS-i-j-k and CPL-i-j-k are respectively used. i, j, and k respectively stand for the number of the stories, the bay of the frame and the earthquake directed to the frame. The value of k for Elcentero, Tabas and Manjil horizontal ground-motion components is 1, 2, and 3 respectively. For example a 10-story 3-bay frame with a RBS connection under Elentero is indicated as RBS-10-3-1.

The height of all stories equals and the size of the bay (axis to column axis) equals 5m are considered to be 3.2 and 5m respectively. Also linear dead load equals 3000kg/m and live load equals 1000kg/m are used in planning and analysis. 3-bay modeled frames are shown in figure 3. The used section in modeling is also shown in table 2. In other models the beam and column sections aren't changed and only the numbers of bays are increased.

Analyzed models have 3, 5 and 7 bays and 5 and 10 stories. (In figure 2-a only three –bay models are shown). 5-story and 10-story models have 3, 5, and 7 bays. Each model is analyzed under three Elentero, Tabas and Manjil spectra and totally 18 dynamic non-linear time-history analyses were done.

2.4 The Definition of Plastic Hinges

The basis for non-linear analysis in the SAP2000 software is plastic hinge theory. After making models, these hinges will be defined on the elements in regard with the place of the formation of the plastic hinges (concerning the kind of connection) and also the nature of the plastic hinges (moment, axial force, moment and axial force interaction). For defining beam bending joints, the calculated rotation and moment values are considered into the computation in regard with the connection behavior. In defining beam bending joints all joints are specified to all beams and no default is used. The curve at the primary region has got an initial stiffness and the value of stiff hardening strain concerning a steep equals 3% elastic parts. Words such as IO, LS and CP which are shown in figure 4 are actually the behavioral levels which are defined FEMA (FEMA 356 2000) to control the shape of parts for different operational goals (IO: Immediate Occupancy, LS: Life Safety, CP: Collapse Prevention). Top and bottom flange cover plate connection (CPL) is one of the most popular connections in Iran. The FEMA proposed values are used for modeling the amount of the rotation of the connection, the modeling parameters of this kind of connection and its comparison with RBS connection (FEMA 356 2000). According to proposed values CPL connection can only be regarded as controlled connections by the deformation, if no fracture happens in the weld and the reduction of resistance in the connection is just because of the yielding of the top and the bottom plates (FEMA 356 2000).

Here for modeling the most ductile kind of CPL connection is used. For RBS connections modeling the rules existing in the FEMA are used. For designing RBS connections the rules existing in FEMA are used which are mentioned in part 2-2(Engelhardt M. D et al. 1998 & FEMA 356 2000). "a", "b", and "c" values for used beam sections are given in table 2. For example, the used specifications for modeling beam plastic hinge are shown in table3. Defined parameters are shown in table 3 and figure 1. For modeling plastic hinges of columns in both CPL and RBS, the same plastic hinge specifications are used, because the specifications of the plastic hinge of the column changes if the beam- column joint changes. The type of the joint was modeled and determined by considering directed loads to the structure (controlled by force or by deformation) (FEMA 356 2000).

For modeling the way plastic hinges are formed in RBS connection, it was assumed that plastic hinge in RBS connection expands in the middle of reduced area. And about CPL connection, it was assumed that the plastic hinge expands from the connection plates and in the critical area (near the column face). As a result the place of plastic hinge was specified according to the specifications of each kind of joint. In table 4 the manner of locating plastic hinge in a sample of 10-story models is examined. Using RBS connection increases the amount of the rotation and makes the plastic hinge go away from the column.

4. Studying the Results of Dynamic Non-Linear Analysis of Frames

Here the results will be investigated. For investigation different parameters can be used. First the plastic hinges formation process in two similar frames having RBS and CPL connections are considered. For example, the expanding process of plastic hinges in CPL-10-5-2 and RBS-10-5-2 are considered (Figure3). This study is carried out at the time of maximum displacement in the frame under the Tabas earthquake spectrum (which has happened in 10 stories - 5 bays frames in 9.86 seconds).

Figure 3 shows that beams in frames with RBS connection are more in plastic area in comparison to CPL connection and also columns in frames with RBS connection in comparison to frames with CPL connection are less in plastic area. As it can be observed in table 5, making RBS connection reduces the number of IO connections from 31 in CPL to 23 in RBS connection. In general it also reduces the number of E joints from 8 in CPL connection to 6 in RBS connection. Also making RBS connection reduces base shear and imposed forces to the column. The results of this comparison are shown in table 5.

As it can be observed in table 6, making RBS connection reduces the number of IO hinges in all models and increase the number of LS hinges. In general, making RBS connection also reduces the number of E joints. Also making RBS connection reduces base shear and imposed forces to the column. Time parameter exhibits the peak time that in each cases top level reaches to maximum displacement (for example in first sample time is equalled to 2.89 sec). It can be inferred that because of reducing the number of IO hinges, this reduced hinges change to LS hinges. It demonstrates that making RBS connection can be improved the behaviour of connections in earthquake.

In order to study the effect of making RBS connection on the frame displacement two parameters namely inter story drift angle abbreviated ISD, and global story drift angle abbreviated GSD are investigated. To get ISD, after analyzing the frame, the displacement of each story is to be subtracted from the downstairs and the diagram is to be drawn. To get GSD, the displacement of each story is divided to the height of that story from the surface of the ground. Then to compare the effect of connection, the ISD and GSD diagrams derived from frames with RBS connection are divided to derived diagrams from the analysis of CPL frames respectively.

Values less than 1 in the diagram show the reduction of ISD or GSD ratio in RBS connection in comparison to CPL connection, and values more than 1 show the increase of ISD or GSD ratio. Then the diagrams derived under three spectra are drawn for both ISD and GSD. The vertical axis of diagram shows the ratio of the height of story divided to the total height of the frame (for example this ratio for the first story of a 5-story frame equals 0.2). Then for more investigations the results of the three ISD or GSD diagrams related to the three spectra are drawn in one diagram and the averaging is done (Figure 4, 5).

As shown in figure 4, in 5-story models, making RBS connection generally reduces the value of ISD and GSD. The important point is that models of making RBS connection causes a more fall in the upper stairs of the frame, and the ratio of reduction in the downstairs is less. The maximum reduction of ISD mean curve (figure 4-a) is 7.1 percent that happens on fourth floor. Also the maximum reduction of GSD mean curve (figure 4-b) for 5-story frames is 5.6 percent which happens on the fourth floor. Figure 5-a shows ISD mean diagram for frames with RBS connection in comparison to frames with CPL connection for all 10- story models. According to this diagram making RBS connection increases the value of ISD in downstairs frames and decreases the value of ISD in upstairs frame. The maximum increase is related to 0.4 of the height (fourth story) which equals 10.2 percent. The maximum reduction equals 16.3 which happen at the 0.9 of the height (ninth floor).

Another important point is that the rate of reduction falls on the last floor, and the ratio of displacement is directed toward unity. In figure 5-b, GSD diagram in frames with RBS connection in comparison to frames with CPL connection is shown. In 10-story models (contrary to 5-story models) making RBS connection increase stories displacement in a height more than 0.2 H (higher than second floor). The maximum displacement in total displacement angle of the frame is in 0.5H (fifth floor) and the amount of increase equals 10 percent whereas, the amount of decrease is little and equals about 3.5 percent. These variations can be due to higher vibration modes in high frames. It also can be due to sudden variation of section which happens on the eleventh floor (Section variation from IPB400 to IPB340). It is because of the fact that GSD is so similar to first vibration mode and the ISD of the resultant of all frame modes is in the analysis. In figure 6-a the overall mean diagram driven from the ISD of all models is given. In this diagram the variation of mean ISD for all models is given along with the height variations. According to this diagram it becomes evident that the reduction of making RBS connection increases the ISD rate of frames in downstairs frames and decreases the ISD rate of upstairs frames. Based on diagram 6-b it also becomes clear that because of the increase of the GSD ratio, generally structure displacement in frames with RBS increases. Of course, making RBS connection causes a little reduction in the downstairs displacement; however except these parts the other parts experience an increase in the displacement.

5. Conclusion

According to the given explanations following conclusions can be drawn:

- Based on the analysis done by SAP2000 and based on plastic hinge theory it was shown that beams in frames with RBS connection enter into the plastic zone more than frames with CPL connection and also columns with RBS connection enter into the plastic zone less than frames with CPL connection.
- The effect of making RBS connection on the amount of variations of lateral Inter story drift angle (ISD) is not the same as the bottom and top cover plates connection (CPL) in different stories. Making RBS connection increases the amount of the Inter story drift angle of the frame in lower parts of the structure (0.4H). The maximum rate of increase equals 4 percent which happen in the height of 0.4H. Also this connection reduces the amount of the inter story drift angle of the frame in upstairs. This amount increases in the last stories again. The maximum amount of reduction is for 0.9H which equals 13 percent.
- Making RBS connection decreases the frame's Global story drift angle (GSD) in most parts except middle stories. The amount of increase is significant in middle stories. The maximum amount of increase equals 3 percent which happen in the height of 0.5H. The maximum amount of reduction is for 0.2H which equals 4 percent.

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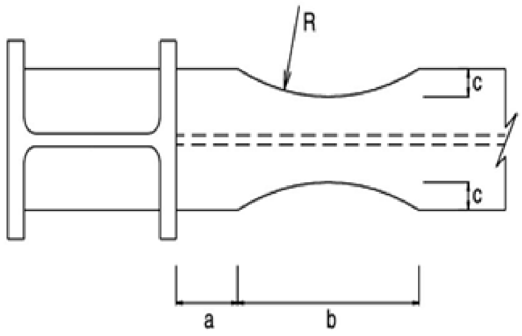


Figure1. Introducing designing parameters in radius cut connection.

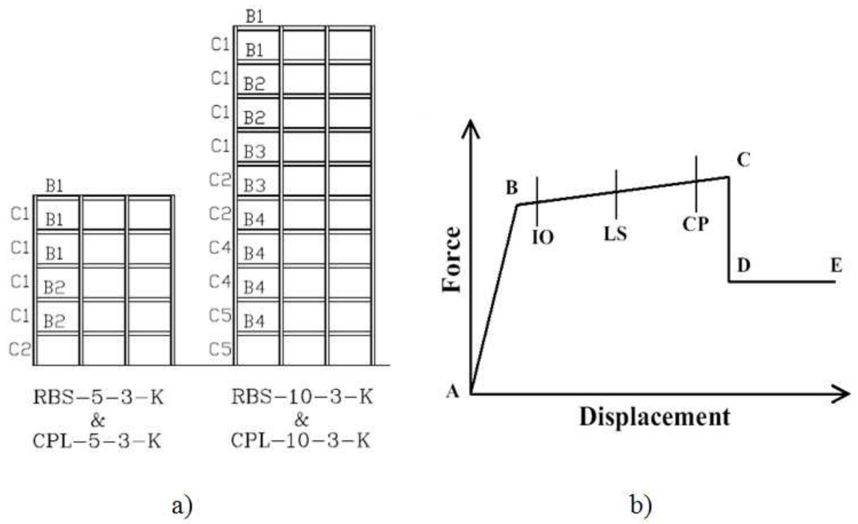


Figure2. a) Designing specifications of analyzed frames under non-linear time history analysis, b) How to define plastic hinges for ductile parts.

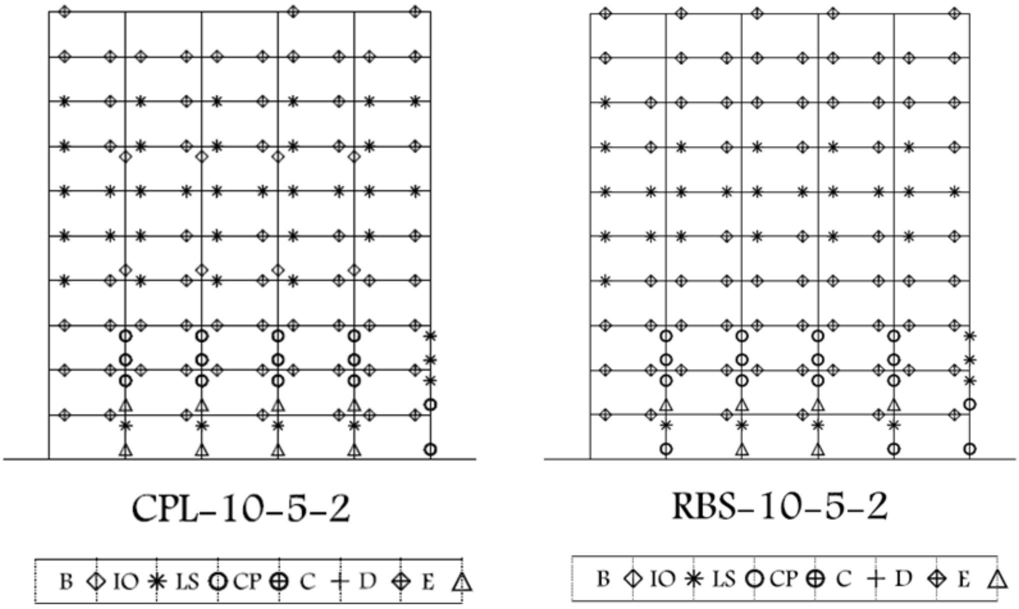


Figure3. The manner of the expansion of plastic hinges in CPL-10-5-2 and RBS-10-5-2 in 9.86 periods (maximum time of displacement on the last story).

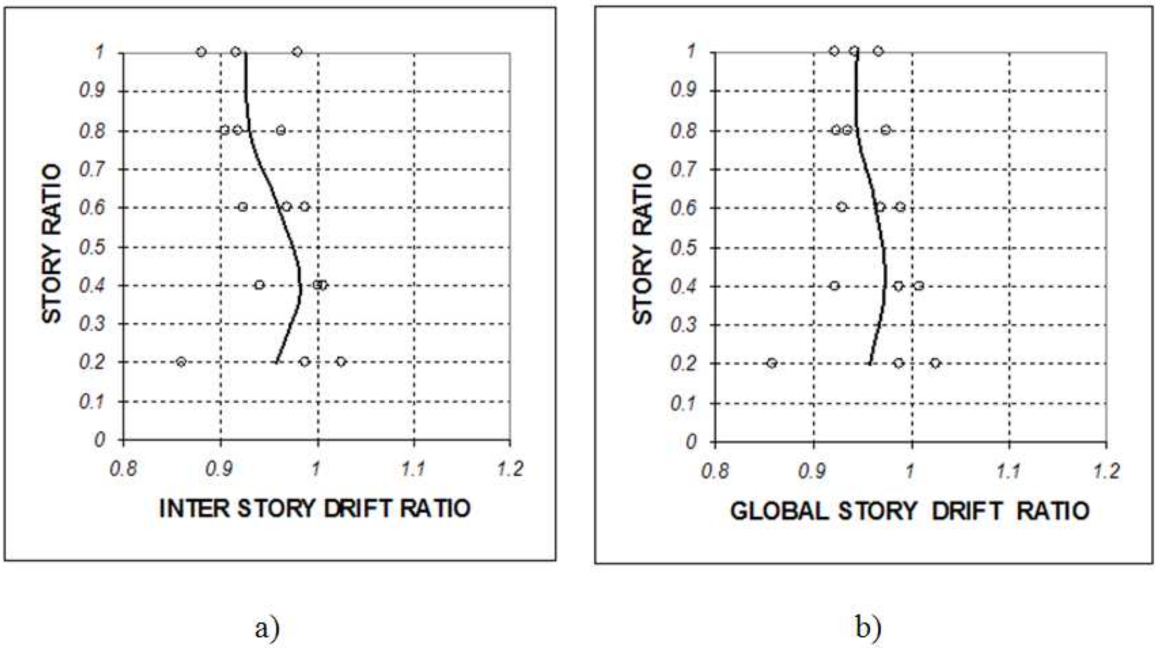
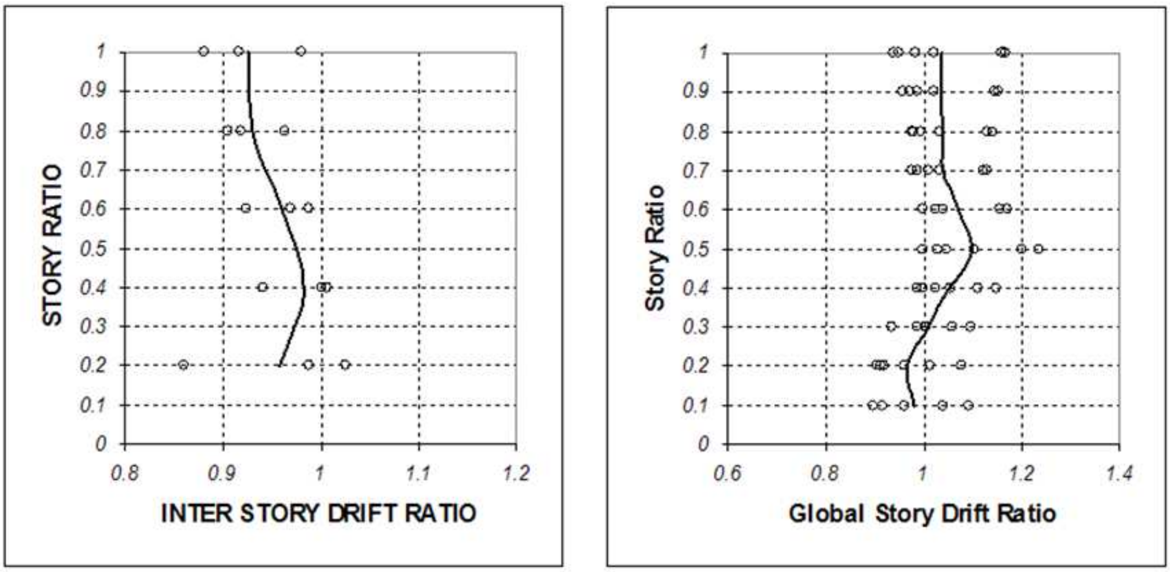
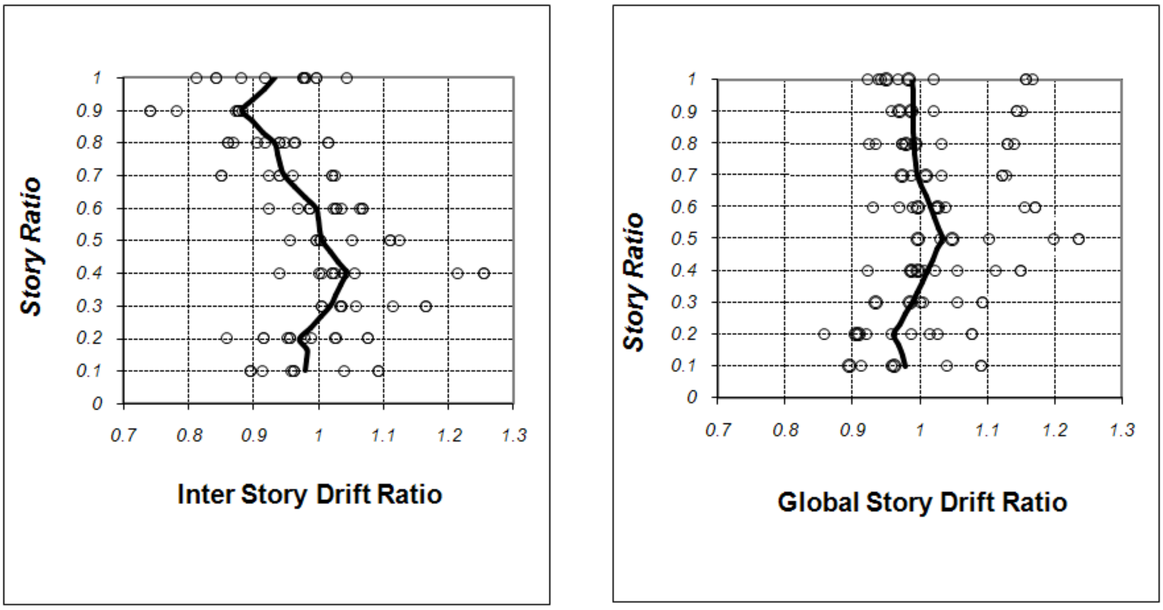


Figure4. Variation diagram, a) ISD, b) GSD for 5-story models.



a) b)

Figure5. Variation diagram, a) ISD, b) GSD for 10-story models.



a) b)

Figure6. Variation diagram, a) ISD, b) GSD for all models.

Table 1.Sections used in analysis.

Column type	Section	Beam type	Section
C1	IPB300	B1	IPE330
C2	IPB340	B2	IPE360
C3	IPB360	B3	IPE400
C4	IPB400	B4	IPE450
C5	IPB550		

Table 2.Cut values for RBS connections for different sections.

Beam section	$a=0.625b_f$(cm)	$b=0.75d_f$(cm)	$c=0.2b_f$(cm)
IPE330	10	24.75	3.20
IPE360	10.625	27.00	3.40
IPE400	11.25	30.00	3.60
IPE450	11.875	33.75	3.80

Table 3. Plastic hinge specifications in RBS and CPL connections beam.

Beam section	TYPE OF CONNECTION	IO	LS	CP	D,C	E
IPE330	RBS	0.0110	0.0350	0.046	0.046	0.066
	CPL	0.0075	0.0228	0.030	0.030	0.060
IPE360	RBS	0.0110	0.0350	0.0457	0.046	0.0657
	CPL	0.0075	0.0228	0.030	0.030	0.060
IPE400	RBS	0.0110	0.0350	0.0452	0.046	0.0652
	CPL	0.0075	0.0228	0.030	0.030	0.060
IPE450	RBS	0.0110	0.0350	0.0446	0.046	0.0646
	CPL	0.0075	0.0228	0.030	0.030	0.060

Table 4.The place of plastic hinge was specified according to the specifications of each kind of joint in 10-story models.

STORY	BEAM	COLUMN	The place of plastic hinge in CPL/Length of the beam		The place of plastic hinge in RBS/Length of the beam	
			Beginning	End	Beginning	End
1	IPE450	IPB450	0.045	0.955	0.1025	0.8975
2	IPE450	IPB450	0.045	0.955	0.1025	0.8975
3	IPE450	IPB400	0.04	0.960	0.0975	0.9025
4	IPE450	IPB400	0.04	0.960	0.0975	0.9025
5	IPE400	IPB340	0.034	0.966	0.0865	0.9135
6	IPE400	IPB340	0.034	0.966	0.0865	0.9135
7	IPE360	IPB300	0.03	0.97	0.07825	0.92175
8	IPE360	IPB300	0.03	0.97	0.07825	0.92175
9	IPE330	IPB300	0.03	0.97	0.07475	0.92525
10	IPE330	IPB300	0.03	0.97	0.07475	0.92525

Table 5.The number of formed joints in CPL-10-5-2 and RBS-10-5-2 in 9.86 periods (maximum time of displacement on the last story).

Models	Type	B	IO	LS	CP	D	C	E
RBS	Beams	67	23	0	0	0	0	0
	Columns	0	7	16	0	0	0	6
CPL	Beams	59	31	0	0	0	0	0
	Columns	8	7	14	0	0	0	8

Table 6. The number of formed joints in CPL and RBS (maximum time of displacement on the last story).

MODEL	**ELCENTRO**	**SMF**			**RBS**		
	TIME	**IO**	**LS**	**E**	**IO**	**LS**	**E**
5-3	2.89	8	0	0	4	0	0
10-3	5.49	53	4	8	46	6	6
10-5	5.49	90	9	14	75	12	10
10-7	8.76	119	6	29	109	18	14
MODEL	**TABAS**	**SMF**			**RBS**		
	TIME	**IO**	**LS**	**E**	**IO**	**LS**	**E**
5-3	14.26	0	0	0	0	0	0
10-3	9.85	25	8	4	24	9	0
10-5	9.86	38	14	8	30	16	6
10-7	14.49	53	20	12	41	20	12
MODEL	**MANJIL**	**SMF**			**RBS**		
	TIME	**IO**	**LS**	**E**	**IO**	**LS**	**E**
5-3	12.08	0	0	0	0	0	0
10-3	11.34	20	9	2	15	7	2
10-5	11.34	31	16	4	23	12	4
10-7	11.35	43	24	7	31	12	12