SEISMIC RESPONSE OF IRREGULAR RC BUILDINGS WITH CRACKED SECTION PROPERTIES

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ABSTRACT

According to the Global Seismic Hazard Map, it has been identified that there is potential threat of earthquake vulnerability in many region of Bangladesh. This poses a great concern for the civil infrastructure as a whole. The previous version of the national building code BNBC 2006 did not emphasize cracked section properties for reinforced concrete (RC) members explicitly while designing the structural components of the building. However, the newer version of BNBC 2020 utilized the cracked section properties for those cases. Therefore, the objective of this paper is to compare the seismic behavior for irregular RC frame systems considering cracked section behavior. Nonlinear static analysis has been used to assess the seismic response in terms of global load-displacement curve, inter-story drift, and ductility parameters. In addition, variation in reinforcement demands in the structural members has been compared. Buildings with 7 to 14 stories with plan irregularities having gross and cracked section properties have been considered in the analyses. Finally, a response modification factor for the framing system has been determined based on the cracked stiffness properties and the obtained values have been compared for those with the gross-section properties. From the analyses, it is observed that buildings with cracked stiffness properties demand higher reinforcements for the columns in comparison to gross-section properties. In addition, the response modification factor resulted in lower values than the gross-section properties.

Keywords: *Nonlinear Static Analysis, Response Modification Factor, Section Properties, RC Buildings*

1. INTRODUCTION

The plan irregularity is always a potential threat to the structural system. However, from the antithetical point of view, the architects considered L-pattern or other framing systems. So, to satisfy the industry demand as well as a seismic vulnerability compliance issue, the structural engineering community has to be focused on stiffness contention during the earthquake phenomenon. Juan et al. (1995) studied unsymmetrical plan-building models on traditional inelastic 3D models to find out the peak response. Rana et al. (2004) accomplished a nonlinear static (pushover) analysis on a 19-storied reinforced concrete tower building in San Francisco and checked Life safety performance under design earthquake. For all the lateral framing members, cracked section stiffness's were assumed to be 50% of the gross-section properties. Ladjinovic et al. (2008) studied seismic behavior on unsymmetrical building plans with asymmetric stiffness and strength distributions. Ravikumar et al. (2012) studied the structural performance of different asymmetric buildings in rocky soil in India. Haque et al. (2016) carried out a study on the seismic performance of 3nos- 3-regular and 1nos- 1-irregular building models with plan irregularity. Irwan et al. (2018) conducted a study on fixed and isolated I-shaped buildings. Butt et al. (2019) considered shear walls as well as bracings to compare between the symmetrical and unsymmetrical structures dealing with the response spectrum method. They conducted the study on 10-storied different building models with various shapes of shear walls and reinforcement layouts. Firoj et al. (2019) conducted the response spectrum analysis of an irregular 10-storied building in seismic zone-v to find out joint displacement, axial forces, time period, and mass participating factors. Farhan et al. (2019) investigated the seismic analysis of multi-storied RC buildings with regular and irregular plans having re-entrant corners. Patil et al. (2020) anticipated research of torsional effects on unsymmetrical RC frame buildings to minimize the torsion ratio limit. An L-shaped 16-storied building was analyzed with ETABS software. All the above literature shows an effect on the concern for an irregular plan of the buildings.

In BNBC-2006, there was no provision outlined explicitly for RC members regarding cracked stiffness for the structural behaviour. On the other hand, BNBC-2020 has considered cracked section properties of RC members in factored design. For beam I_g= 35% of gross inertia and column I_g= 70% of gross moment of inertia has been utilized for the factored design. The main objective of this paper is to assess the seismic behaviour of RC irregular plan buildings considering the gross and cracked section properties. The seismic performance, drift check, and response modification factor (R) have been evaluated with the nonlinear pushover analysis (NLPA).

2. BUILDING MODELS

Nonlinear Static Pushover Analysis (NSPA) Capacity Spectrum Method(CSM) has been accomplished for the irregular building designed as per BNBC-2020. In the present study, the all irregular RC frames is to be considered for rigid floor diaphragms. Plan irregularity has been assessed as per BNBC 2020. 7 to 14 storied buildings with irregular plan have been considered in the current study. All the building models have been analyzed using finite element software ETABS. Nonlinear static analyses(CSM) on the building models have also been conducted using ETABS. To develop spectral acceleration vs. spectral displacement curve from the global pushover curves following equations have been used:

$$S_{ai} = \frac{V_l / W}{\alpha_l} \quad (1)$$

$$S_{di} = \frac{\Delta_{roof}}{\left(PF_l * \phi_{lroof}\right)} \quad (2)$$

Tables 1 and 2 present the different parameters used in building models and seismic loads, respectively, for the considered building models. Figure 1 shows the plan view of the irregular buildings. Figures 2 to 5 show the elevation of the considered buildings.

Table 1: Parameters for Irregular RC building models

Specification/Parameter	**Details**
Concrete Grade	24 MPa
Steel Grade	420 MPa
Slab Thickness	125 mm
Brick Wall Perimeter	250 mm
Internal Brick Wall	125 mm
Support Condition	Fixed
Dead Load	11.97 kN/m^2
Live Load	2.0 kN/m^2
Seismic Zone	(Dhaka)II
Soil Type	SC
Response Modification Factor	5
Damping	5%

Table 2: Seismic criteria of RC Irregular Frames

Frame	**Height(m)**	**T_a(s)**	**W(kN)**	**S_a**	**V (kN)**
7-Storey	21	0.69	28519	0.056	1428
9-Storey	27	0.89	37247	0.046	1702
12-Storey	36	1.19	50525	0.0365	1820
14-Storey	42	1.39	60978	0.032	1912

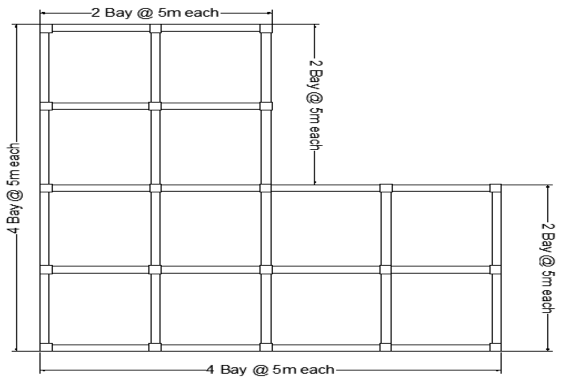


Figure 1: Plan view of Irregular Buildings

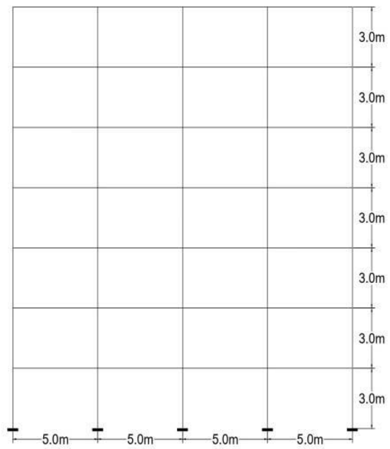


Figure 2: 7- Storey Building Elevation

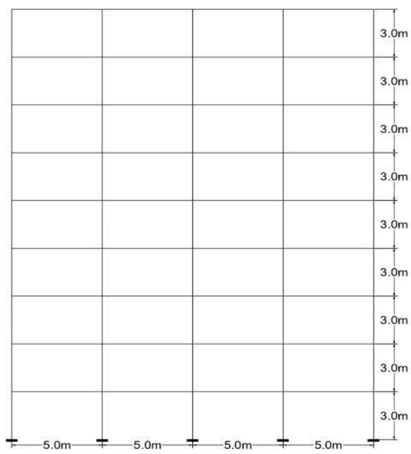


Figure 3: 9- Storey Building Elevation

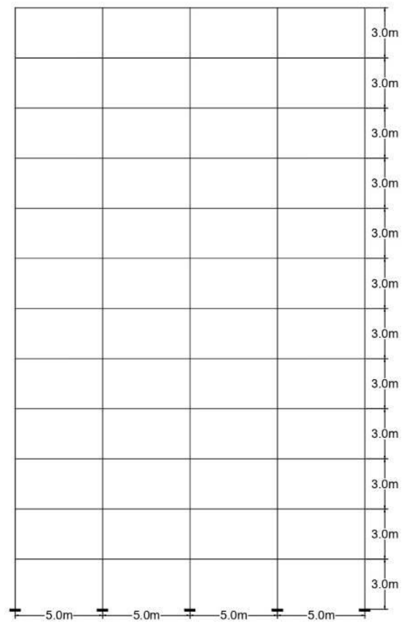


Figure 4:12- Storey Building Elevation

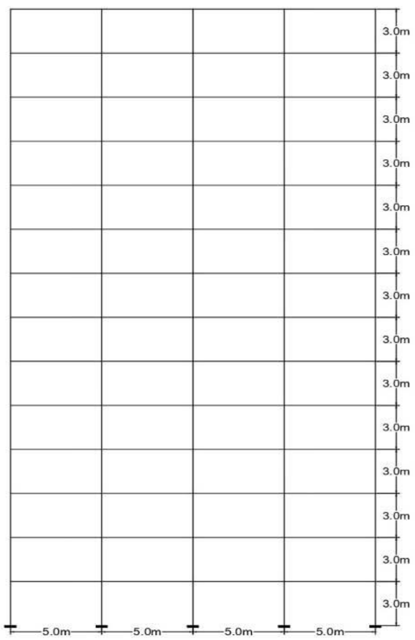


Figure 5: 14- Storey Building Elevation

3. RESULT AND DISCUSSIONS

Structural analysis and design of buildings have been conducted using equivalent static analysis as per BNBC-2020. Table 3 shows the seismic performance evaluation for 7 to 14-storied buildings under design basis earthquake. Comparison is also made using the gross and cracked section properties of the structural members. Table 4 to 7 provide the reinforcement demand for the considered buildings having the cracked and gross section properties. From the analysis results, it is observed that reinforcement demand for the RC columns with cracked sections is usually higher than those with the gross sections. It is also observed that the increase in the reinforcement demand is higher for exterior and corner columns than those of the interior columns. However, for RC beams, this reinforcement demand is comparable when gross and cracked sections are compared. Torsional irregularities have been checked however it was found within the scope of inherent torsion.

Table 3 : Seismic Performance Evaluation for Irregular Buildings

Building Storey Type	**Performance**	**Performance Point**	
	(DBE)	**(V/W)**	**D(mm)**
7-st Gross	IO	0.088	99
7-st Cracked	IO	0.069	169
9-st Gross	IO	0.072	130
9-st Cracked	IO	0.0672	220
12-st Gross	IO	0.0578	264
12-st Cracked	IO	0.0425	360
14-st Gross	IO	0.0378	182
14-st Cracked	LS	0.0372	334

Table 4 **:** Details of reinforcement demands using gross and cracked section properties of 7-storied building

Members	**Floor**	**Width (mm)**	**Depth (mm)**	**Reinforcement Gross section (mm^2)**	**Reinforcement Cracked section (mm^2)**	**% increase in reinf. for cracked section**
Beam (Edge)	1-3	300	500	1196(top)	1163(top)	-2.8%
				659(bot)	639(bot)	-3.1%
Beam (Edge)	4-7	300	500	1093(top)	1071(top)	-2.1%
				636(bot)	613(bot)	-3.8%
Beam (Middle)	1-3	300	500	1236(top)	1124(top)	-9.9%
				586(bot)	587(bot)	0.2%
Beam (Middle)	4-7	300	500	1017(top)	1061(top)	4.1%
				483(bot)	556(bot)	13.1%
Corner Col^m(C1)	0-1	350	350	3292	4000	17.7%
Corner Col^m(C1)	1-2	350	350	2359	2733	13.7%
Corner Col^m(C1)	2-3	350	350	1838	2033	9.6%
Corner Col^m(C1)	3-4	350	350	1265	1553	18.5%
Corner Col^m(C1)	4-7	350	350	1265	1265	-
Edge Col^m(C2)	0-1	400	400	5267	6081	13.4%
Edge Col^m(C2)	1-2	400	400	3703	4107	9.8%
Edge Col^m(C2)	2-3	400	400	1845	1909	3.4%
Edge Col^m(C2)	3-7	400	400	1652	1652	-
Middle Col^m(C3)	0-1	450	450	6416	7527	14.8%
Middle Col^m(C3)	1-2	450	450	3256	3469	6.1%
Middle Col^m(C3)	2-7	450	450	2090	2090	-

Table 5: Details of reinforcement demands using gross and cracked section properties of 09-storied building

Members	**Floor**	**Width (mm)**	**Depth (mm)**	**Reinforcement Gross section (mm^2)**	**Reinforcement Cracked section (mm^2)**	**% increase in reinf. for cracked section**
Beam (Edge)	1–5	300	500	1340(top)	1270(top)	-5.5%
				711(bot)	674(bot)	-5.5%
Beam (Edge)	6–9	300	500	1077(top)	1028(top)	-4.8%
				631(bot)	605(bot)	-4.3%
Beam (Middle)	1–5	300	500	1272(top)	1137(top)	-11.9%
				500(bot)	550(bot)	9.1%
Beam (Middle)	6–9	300	500	981(top)	849(top)	-15.5%
				458(bot)	508(bot)	9.8%
Edge Col^m(C2)	0-1	450	450	5572	6325	11.9%
Edge Col^m(C2)	1-2	450	450	3483	3802	8.4%
Edge Col^m(C2)	2-3	450	450	2090	2090	-
Edge Col^m(C2)	3-4	450	450	2090	2090	-
Edge Col^m(C2)	4-9	450	450	2090	2090	-
Middle Col^m(C3)	0-1	500	500	6829	7812	12.6%
Middle Col^m(C3)	1-2	500	500	3302	3778	12.6%
Middle Col^m(C3)	2-3	500	500	2581	2581	-
Middle Col^m(C3)	3-9	500	500	2581	2581	-
Corner Col^m(C1)	1-2	400	400	2961	3906	24.2%
Corner Col^m(C1)	2-3	400	400	2655	2881	7.8%
Corner Col^m(C1)	3-4	400	400	1652	1652	-
Corner Col^m(C1)	4-9	400	400	1652	1652	-

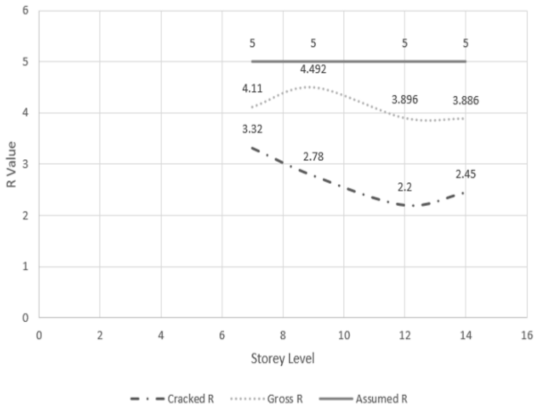
Table 6: Details of reinforcement demands using gross and cracked section properties of 12-storied building

Members	**Floor**	**Width (mm)**	**Depth (mm)**	**Reinforcement Gross section (mm^2)**	**Reinforcement Cracked section (mm^2)**	**% increase in reinf. for cracked section**
Beam (Edge)	1-5	300	600	1445(top)	1373(top)	-5.2%
				955(bot)	883(bot)	-8.2%
Beam (Edge)	6-9	300	600	1336(top)	1267(top)	-5.4%
				846bot)	781(bot)	-8.3%
Beam (Edge)	10-12	300	600	931(top)	876(top)	-6.3%
				595(bot)	569bot)	-4.6%
Beam (Middle)	1-5	300	600	1351(top)	1213(top)	-11.4%
				690(bot)	588(bot)	-17.3%
Beam (Middle)	6-9	300	600	1228(top)	1106(top)	-11%
				577(bot)	560(bot)	-3%
Beam (Middle)	10-12	300	600	798(top)	709(top)	-12.6%
				458(bot)	456(bot)	-.4%
Corner Col^m(C1)	0-1	500	500	4595	5131	10.5%
Corner Col^m(C1)	1-2	450	450	3333	3436	2.1%
Corner Col^m(C1)	2-3	450	450	2090	2090	-
Corner Col^m(C1)	3-4	450	450	2090	2090	-
Corner Col^m(C1)	4-5	450	450	2090	2090	-
Corner Col^m(C1)	5-12	450	450	2090	2090	-
Edge Col^m(C2)	0-1	550	550	7644	8819	13.3%

Edge Col^m(C2)	1-2	500	500	5398	6016	10.3%
Edge Col^m(C2)	2-3	500	500	3409	3499	2.6%
Edge Col^m(C2)	3-4	500	500	2581	2581	-
Edge Col^m(C2)	4-5	500	500	2581	2581	-
Edge Col^m(C2)	5-12	500	500	2581	2581	-
Middle Col^m(C3)	0-1	600	600	9026	10535	14.3%
Middle Col^m(C3)	1-2	550	550	5779	6371	9.3%
Middle Col^m(C3)	2-3	550	550	3801	3878	2%
Middle Col^m(C3)	3-4	550	550	3123	3123	-
Middle Col^m(C3)	4-5	550	550	3123	3123	-
Middle Col^m(C3)	5-12	550	550	3123	3123	-

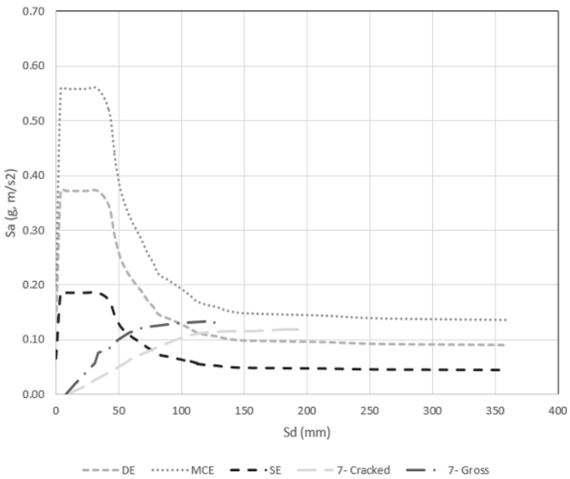
Table 7: Details of reinforcement demands using gross and cracked section properties of 14-storied building

Members	**Floor**	**Width (mm)**	**Depth (mm)**	**Reinforcement Gross section (mm^2)**	**Reinforcement Cracked section (mm^2)**	**% increase in reinf. for cracked section**
Beam (Edge)	1-9	300	600	1532(top)	1452(top)	-5.5%
				1057(bot)	950(bot)	-11.3%
Beam (Edge)	10-12	300	600	1276(top)	1094(top)	-16.6%
				760bot)	624(bot)	-21.8%
Beam (Edge)	13-14	300	600	928(top)	753(top)	-23.2%
				573(bot)	520bot)	-10.2%
Beam (Middle)	1-9	300	600	1398(top)	1233(top)	-13.4%
				730(bot)	634(bot)	-15.1%
Beam (Middle)	10-12	300	600	1050(top)	891(top)	-17.8%
				473(bot)	553(bot)	14.5%
Beam (Middle)	13-14	300	600	695(top)	678(top)	-2.5%
				458(bot)	427(bot)	-7.3%
Corner Col^m(C1)	0-1	550	550	4949	5433	8.9%
Corner Col^m(C1)	1-2	500	500	3425	3338	-2.6%
Corner Col^m(C1)	2-3	500	500	2581	2581	-
Corner Col^m(C1)	3-4	500	500	2581	2581	-
Corner Col^m(C1)	4-5	500	500	2581	2581	-
Corner Col^m(C1)	5-14	500	500	2581	2581	-
Edge Col^m(C2)	0-1	600	600	9382	9510	1.4%
Edge Col^m(C2)	1-2	550	550	5862	6497	9.8%
Edge Col^m(C2)	2-3	550	550	3937	4150	5.1%
Edge Col^m(C2)	3-4	550	550	3123	3123	-
Edge Col^m(C2)	4-5	550	550	3123	3123	-
Edge Col^m(C2)	5-14	550	550	3123	3123	-
Middle Col^m(C3)	0-1	650	650	9201	10892	15.5%
Middle Col^m(C3)	1-2	600	600	6081	6798	10.6%
Middle Col^m(C3)	2-3	600	600	4023	4515	10.9%
Middle Col^m(C3)	3-4	600	600	3716	3716	-
Middle Col^m(C3)	4-5	600	600	3716	3716	-
Middle Col^m(C3)	4-5	600	600	3716	3716	-
Middle Col^m(C3)	5-14	600	600	3716	3716	-



Seismic performance in terms of global pushover curves has been determined for each building model. Response reduction factor, R has been evaluated for such buildings. Analysis results of pushover curves are presented in Figures 6 to 9 for 7-storied to 14-storied buildings, respectively. Figures 6 to 9 also show the seismic performance level at Serviceability Earthquake (SE), Design Basis Earthquake (DBE), and Maximum Considered Earthquake (MCE). Response modification factor has been provided in Fig. 10. Inter-storey Drift analysis comparison has been provided in Figures 11 to 14.

Figure 6: S_a vs S_d of 7-storied building



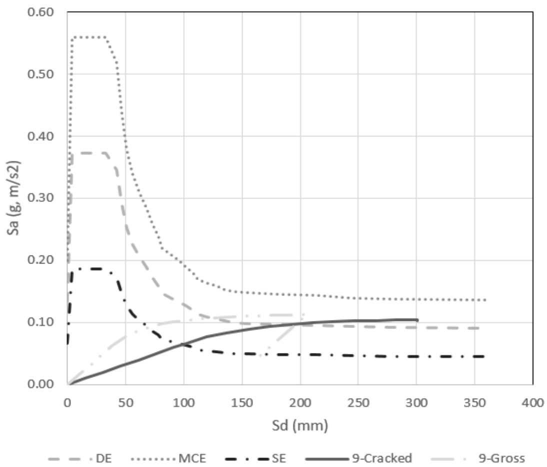


Figure 7: S_a vs S_d of 9-storied building

Figure 9: S_a vs S_d of 14-storied building

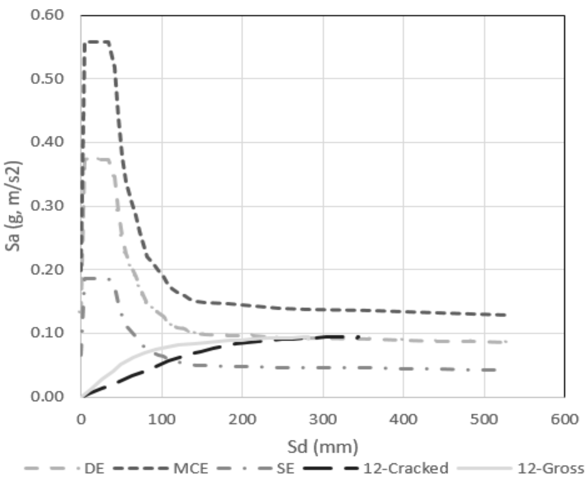


Figure 8: S_a vs S_d of 12-storied building

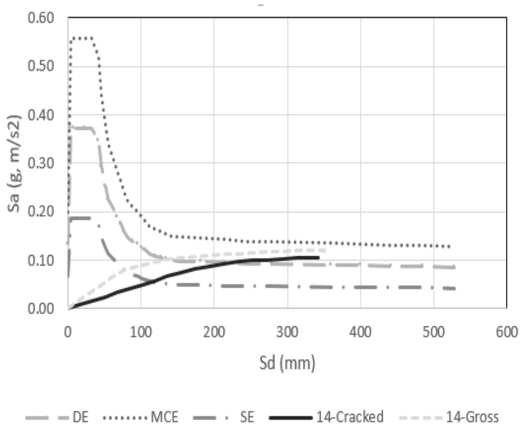


Figure 9: S_a vs S_d of 14-storied building

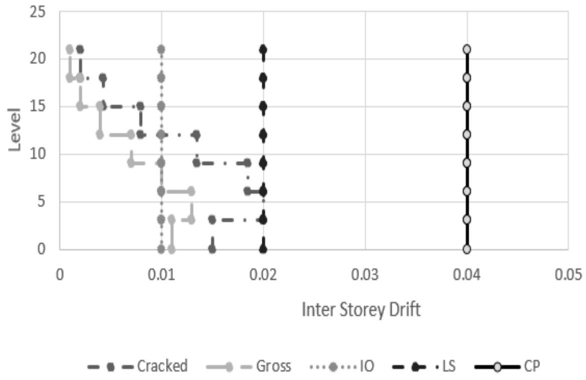
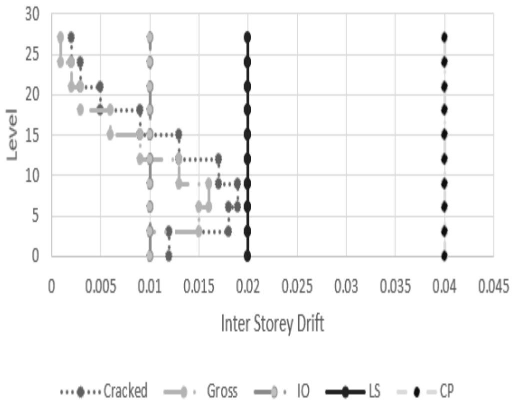


Figure 8: S_a vs S_d of 12-storied building

Figure 10: Comparison of R between Cracked and Gross section.

Figure 11: Inter-storey Drift Comparison in between 7-storied Cracked and Gross section



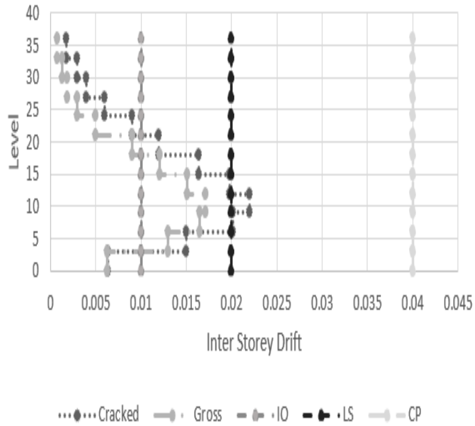


Figure 12: Inter-storey Drift Comparison in between 9-storied Cracked and Gross

Figure 13: Inter-storey Drift Comparison in between 12-storied Cracked and Gross

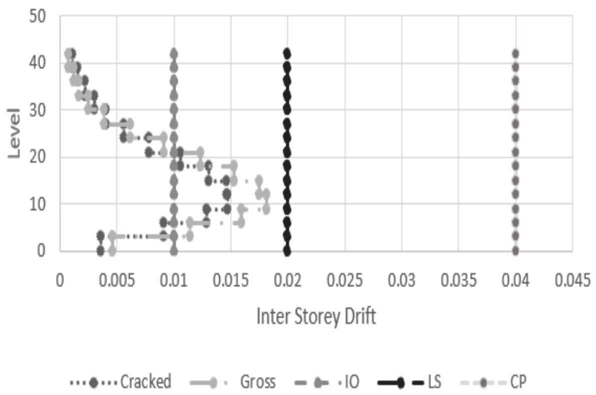


Figure 14: Inter-storey Drift Comparison in between 14-storied Cracked and Gross section

In figure 11 to 14, the result of the NLSPA show that the achieved inter-storey drift at design load for considered 7,9,12,14 storey RC irregular frame designed with gross-section property is well within the prescribed limit at the Life Safety(LS) regime however, inter-storey drift executed for the 7,9,12,14 storey RC irregular frame designed with cracked section is audited substantially higher as compared to RC irregular frame using gross-section and exceeds the prescribed drift limit and observed at Collapse Prevention(CP) regime for the 12-storied Cracked section building given by Bangladesh National Building Code(BNBC-2020). .

4. CONCLUSIONS

The main objective of this paper is to assess the seismic behavior and performance for irregular RC frame systems considering cracked section behavior. Nonlinear static analysis(CSM) has been conducted using finite element software ETABS. 7 to 14 storied building with an irregular plan shape has been considered. All the buildings have been designed as per BNBC 2020 with and without cracked stiffness properties, Following are the main conclusions from the current study:

i) Reinforcement demand for the columns of the buildings increases when cracked stiffness properties have been considered. This demand is increased as high as 24% for some of the columns in the 9-storied building.
ii) Buildings with cracked section properties resulted in lower R values than those with the gross-section properties for the considered buildings.

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