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Evaluation of Seismic Performance of RC Frame Building with Variation in Effective Stiffness

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Abstract

Due to cracking, there will be a substantial reduction in flexural stiffness which ultimately results in larger deflections. Member stiffness is commonly considered as the gross stiffness, or as the effective stiffness which is an approximate percentage of gross stiffness, in the study and design of reinforced concrete (RC) buildings. NBC 105:2020 recommends the use of effective stiffness of cracked sections during analysis, however it is not addressed in NBC 105:1994. Several configurations of moment-resisting frames, regular in plan and elevation, with variation in the number of bays and storey number are designed and analyzed by using gross and cracked section properties. The motive of this research is to study the effect of the modeling approach of building in terms of gross and cracked sections on the structural performance under earthquakes. Non-linear static analysis is done in ETABSv19 to evaluate the overstrength and ductility of structures designed using gross and cracked section properties.

Keywords

Effective stiffness, Overstrength factor, Ductility factor

1. Introduction

Cracking is an inevitable phenomenon in concrete structures resulting from various factors such as applied loads, shrinkage, thermal load and settlement in the structure. When concrete is in tension, if tensile stress of a particular element grows beyond rupture stress, cracking will occur and that element will not have the same stiffness as it used to have prior to cracking. It would be ideal if the member stiffness reflected the degree of cracking caused by applied loads to each member.

As a result of cracking, flexural stiffness will be significantly reduced. The lateral deflection of reinforced concrete members increases as the flexural stiffness value decreases, and it can be far more than the deflection anticipated using gross flexural stiffness. It is very crucial to estimate the flexural stiffness of individual components so as to capture the dynamic properties of a structure as well as the force versus deformation demands. The parameters like time period, deflection, internal force distribution and overall dynamic response of the structure are affected due to change in stiffness. Therefore, it is essential to use the reduced or effective stiffness of the reinforced concrete structure. It is practically impossible to retain the uncracked stiffness of a structural member during or after a seismic response. Thus, it can be inferred that uncracked stiffness is not an accurate estimate of the effective stiffness. Moreover, using uncracked stiffness results in inaccurate estimation of seismic forces as well as incorrect force distribution across the structure [1].

To take these effects into consideration, the design code of several countries suggests some reduction factors or equations to reduce the gross stiffness to effective stiffness. In Nepal National Building Code NBC 105:1994, there were no provisions to account for the reduction in stiffness due to concrete cracking [2]. However, the new revised NBC 105:2020 recommends effective moment of inertia of 70% of I_{gross} of columns and 35% of I_{gross} of beams for the analysis of RC frame structures [3]. Furthermore, a rational analysis is suggested to estimate the elastic flexural and shear stiffness properties of cracked concrete. The effective moment of inertia of beams and columns suggested in different international standards is listed in Table 1.

Table 1: Effective moment of inertia of beams and columns suggested in different international standards [4, 5, 6, 7].

Codes	Beams	Columns	Wall uncracked	Wall cracked
NBC 105:1994	No Provision			
IS 1893:2016	0.35 Ig	0.70 Ig	-	-
NZS 3101	0.35 Ig - 0.4 Ig	0.40 Ig - 0.80 Ig	n/a	0.32 Ig - 0.48 Ig
ACI 318-19	0.35 Ig	0.7 Ig	0.7 Ig	0.5 Ig
Eurocode-8	0.5 Ig	0.5 Ig	0.5 Ig	0.5 Ig
ASCE 41-13	0.30 Ig	0.7 Ig	n/a	0.5 Ig
FEMA 356	0.5 Ig	0.5Ig - 0.7 Ig	0.8 Ig	0.5 Ig

Table 2: Effective stiffness of different components (NBC 105:2020)

S.No.	Component	Flexural stiffness	Shear stiffness
1.	Beams	0.35 E_cI_g	0.40 E_cA_w
2.	Columns	0.70 E_cI_g	0.40 E_cA_w
3.	Wall un-cracked	0.80 E_cI_g	0.40 E_cA_w
4.	Wall cracked	0.50 E_cI_g	0.40 E_cA_w

2. Gross and Cracked Section

Basically, there are two approaches that can be adopted for the design of concrete structures i.e., gross and cracked section. In an uncracked section, the member is loaded up to the point of cracking but remains uncracked and the stress distribution is assumed to be linear whereas in the case of cracked section non-linear stress distribution is assumed.

2.1 Gross Section

The bending tensile stress in concrete is minimal when the value of the applied moment is small. As a result, the applied moment in an uncracked section is less than the cracking moment (M_{cr}), and the tensile stress is less than the flexural tensile strength (f_{cr}). This is referred to as the uncracked phase, and it occurs when the entire section is effective in resisting the moment and is under stress.

2.2 Cracked Section

In the case of cracked section, the value of applied moment exceeds the cracking moment (M_{cr}), causing the appearance of cracks in the tension zone of the concrete member and as a result of which the concrete is unable to withstand tension anymore. Any further increase in the applied moment must be accounted for entirely by the reinforcing steel. The comparatively large increase in the tensile strain of reinforcement causes the neutral axis to shift upward.

3. Overstrength and Ductility factor

Generally, structures are designed to resist a much higher strength than what is required. It has become a normal practice to provide members with greater sizes and higher material strengths than the minimal design requirements estimated using the design codes. The overstrength factor (Ω) can be defined as the ratio of the first significant yield strength of the structure to the design base shear of the structure.

$$\Omega = \frac{V_y}{V_d} \tag{1}$$

Ductility is the capacity of a structure to withstand a large deformation without undergoing failure. In structural engineering, the displacement ductility ratio (μ) and ductility reduction factor (R_μ) are widely used to define the ductility of a structure. Furthermore, ductility is often used in earthquake engineering to indicate a structure's capability to sustain massive lateral displacements caused by strong ground motion during an earthquake. The displacement ductility ratio (μ) is the ratio of the system's highest absolute relative displacement to its yield displacement, and it represents the amount of inelastic deformation experienced by the system under a given ground motion [8].

$$\mu = \frac{Max\left|\mu\left(t\right)\right|}{\mu y} \tag{2}$$

The equation proposed by Miranda and Bertero is:

$$\phi = 1 + \frac{1}{12\mathrm{T} - \mu\mathrm{T}} - \frac{2}{5T} exp\left[-2\left(lnT - \frac{1}{5}\right)^2\right] \tag{3}$$

$$R_\mu = \frac{\mu - 1}{\phi} + 1 \tag{4}$$

ϕ = function required to calculate approximate strength-reduction factor

T = Period of vibration

4. Model Selection

Regular, symmetric in plan and elevation RC frame buildings in which the number of storeys varied from 2 to 6 were considered in this study. Different assumptions were made in order to reduce complexity during analysis. The general assumptions that were considered while modeling is listed below.

- The foundation is assumed to be rigid i.e., soil structure interaction is not considered.
- The beam rests centrally on the column so as to avoid the local eccentricity.
- The size of the beam and column is kept constant throughout the building.
- Rigid Diaphragm is assumed.
- The effect of non-structural components like staircase is assumed to be negligible.
- Secondary effects such as temperature, creep, shrinkage etc. are not considered.

The parameters were varied by considering each combination based on the following scope.

- Number of storeys considered: 2, 3, 4, 5, 6
- Number of bays considered: 2, 3, 4, 5
- Length of bay: 3.5m
- Storey Height: 3m

Table 3: Design Parameters

Importance Factor	1
Soil Type	Type B - Medium
Concrete Grade	M25
Reinforcement	HYSD 500
Slab Thickness	125mm
Live load	3KN/m^2 on all floors 1.5 KN/m^2 on the roof
Floor finish	1 KN/m^2
Wall load	As UDL on beam
Lateral load	As per NBC 105:2020

Table 4: Column and beam size adopted for different models

No. of storey	Beam size(mm)	Column size(mm)
2	250 × 300	300 × 300
3	250 × 300	350 × 350
4	300 × 400	400 × 400
5	300 × 400	400 × 400
6	300 × 400	450 × 450

5. Methodology

The finite element modeling of the building was done using ETABSv19. Each building was analyzed using gross as well as cracked section properties as per the effective stiffness values suggested in NBC 105:2020 (Table 2). Design base shear and fundamental time period of the building was obtained and the designed building was checked to see if all the members are capable of resisting the applied load.

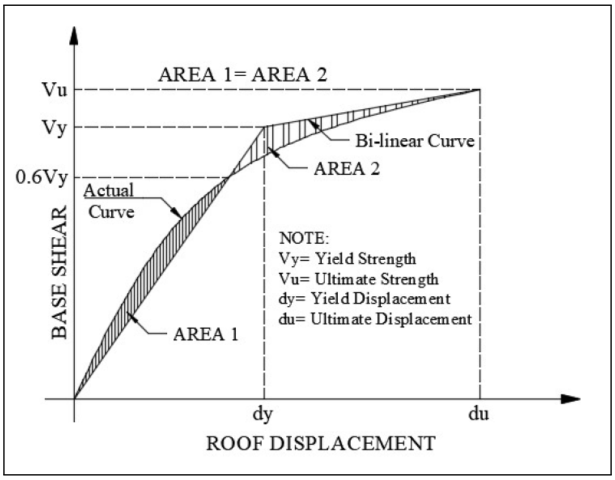

Figure 1: Bilinear Idealization of a pushover curve

Material non-linearities are assumed by defining frame hinge properties as per ASCE 41-13, which represent post-yield behavior [9]. Hinges are placed at the ends of the beam and column where the mechanism is expected. The default hinge is defined for both the beam and the column member. To capture linked axial and biaxial bending behavior, an auto P-M2-M3 hinge was defined for the column. Axial load effects are neglected for beam members due to the rigid floor diaphragm effect, and an uncoupled moment M3 hinge is provided. A pushover curve was obtained which was then converted to get an idealized bilinear curve based on the provisions provided in

FEMA 356:2000 according to which the following two criteria must be fulfilled [10].

1. The line segments on the idealized force-displacement curve must be adjusted so that the area above and below the curve is balanced.
2. The first segment of the bilinear curve must intersect the original curve at 60% of significant yield strength.

6. Results and Discussion

The results obtained from the linear static analysis as well as pushover analysis were evaluated and the result from the representative set of buildings are presented here.

6.1 Effect on Inter-storey Drift

The inter-storey drift was studied by analyzing the models by using gross section and cracked section for analysis and also by varying the number of storeys and number of bays. The variation in inter-storey drift when using uncracked and cracked section for both ultimate limit state as well as serviceability limit state is illustrated in Figure 2 and Figure 3. The response of the analyzed building shows increment in the inter-storey drift for the model designed using cracked section.

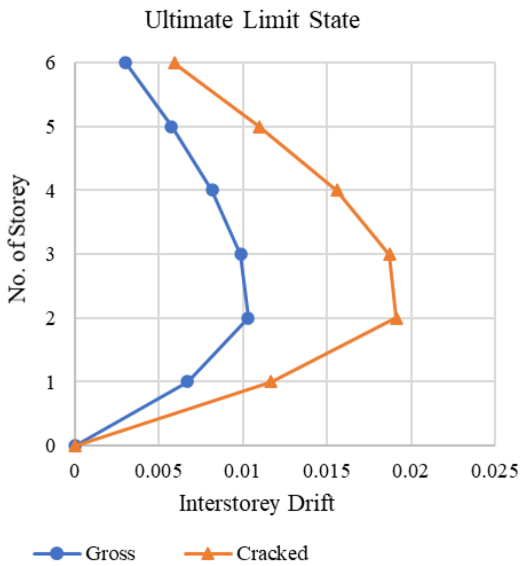

Figure 2: Inter-storey drift for 6 storey model having 4 number of bays (ULS)

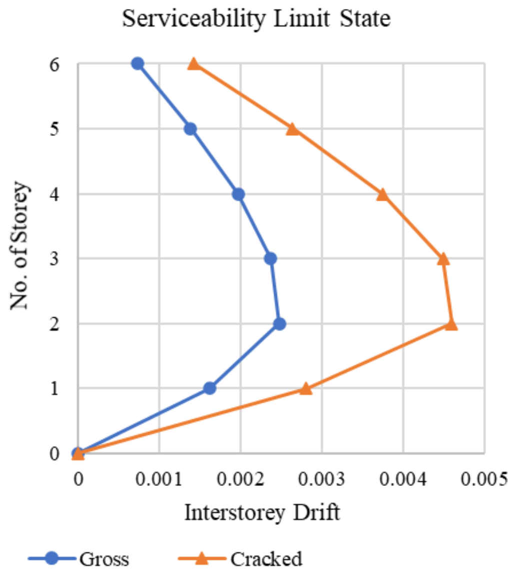

Figure 3: Inter-storey drift for 6 storey model having 4 number of bays (SLS)

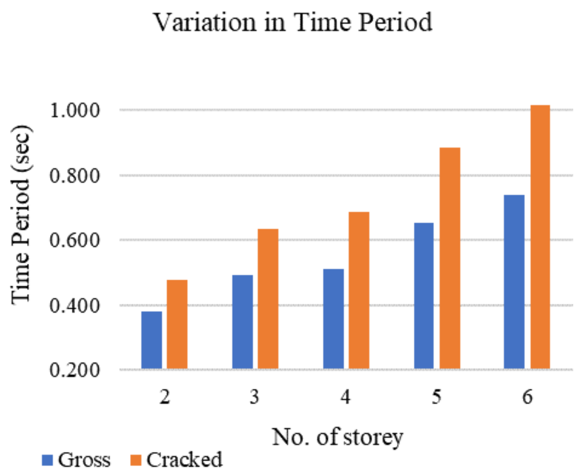

Figure 4: Variation in Time period

6.2 Effect on Time period

For capturing the dynamic properties of a building, proper assessment of the flexural stiffness of individual members is essential. The time period was studied by analyzing the models by using gross section and cracked section. The results indicated that the natural period of a building calculated using gross stiffness is lower than the natural period calculated using effective stiffness. This can be justified by the fact that stiffer buildings have less time period. While reducing stiffness, the mass is also reduced, thus, during the calculation of the natural period, the mass and stiffness compete to decide whether the natural period will increase or decrease when both are modified.

From Figure 4, it is evident that the time period for the cracked section increases as compared to the gross section when the number of storeys is varied. However, the increment in the time period due to an increase in the number of bays is very minimal.

6.3 Effect on Overstrength factor

The overstrength factor was studied by analyzing the models by using gross section and cracked section for analysis and also by varying the number of storey and number of bays. Each of the following graphs presents the overstrength factor of the gross section model and cracked section model with variation in the number of storey and number of bays. The overstrength factor for buildings using gross section was found to be higher than that of cracked section even though it was by a slight margin. The overstrength factor is determined by the yield base shear and the design base shear, but the value of the design base shear was the same in both cases. As the value of the yield base shear for the gross section model was found to be more than the cracked section, the overstrength factor for the gross section was found to be higher.

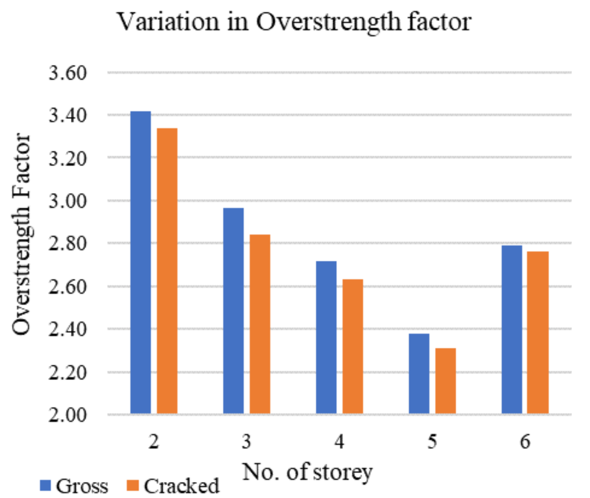

Figure 5: Variation in overstrength factor with increase in number of storeys

From Figure 5, it can be observed that the overstrength factor decreases as the number of storeys increases up to 5 storeys for both gross and cracked section. However, it is evident from the graph that the overstrength factor of 6 storey building is higher than the overstrength factor of 5 storey building. This may be attributed to the fact that overstrength depends upon the yield base shear and the design base shear. An increment in the overstrength factor can be noticed when the yield base shear increases or the design base shear decreases. In this case, the increase in overstrength factor might be primarily due to the decrease in the value of the seismic base shear coefficient as we ascend from 5 to 6 number of storeys. This reduction in the base shear coefficient results in a decrease in design base shear value, which ultimately results in a decline in overstrength in the case of 6 storey building.

6.4 Effect on Ductility factor

Likewise, the ductility factor was studied by analyzing the models using gross section and cracked section, as well as by altering the number of storeys and bays. Figure 6 depicts the ductility factor of a gross section model and a cracked section model with variations in the number of storeys.

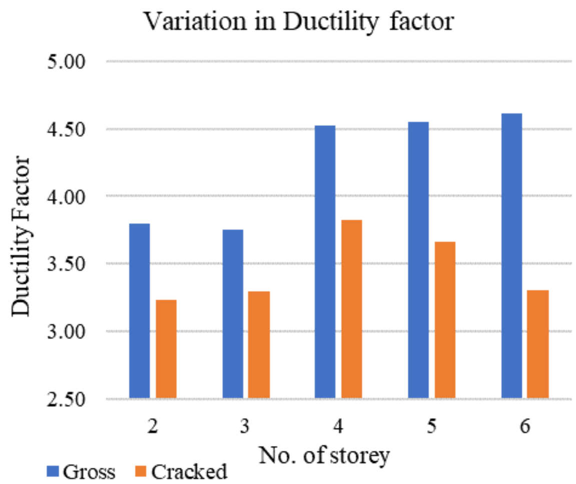

Figure 6: Variation in ductility factor with increase in number of storeys

The value of displacement ductility (μ) was found to be larger for the gross section model as compared to the cracked section model as shown in Table 5. The value of ductility coefficient can also be used to express the inelastic deformation capacity of the structures. The higher the value of this coefficient, the greater the energy absorption and the formation of plastic joints [11].

Table 5: Estimation of yield and ultimate displacement

No. of storey	Gross			Cracked		
	du	dy	µ	du	dy	µ
2	106.62	23.68	4.50	123.33	36.40	3.39
3	137.84	34.69	3.97	165.06	53.76	3.07
4	164.05	34.06	4.82	198.78	57.97	3.43
5	201.66	47.91	4.21	248.71	82.49	3.01
6	252.76	62.72	4.03	308.98	114.41	2.70

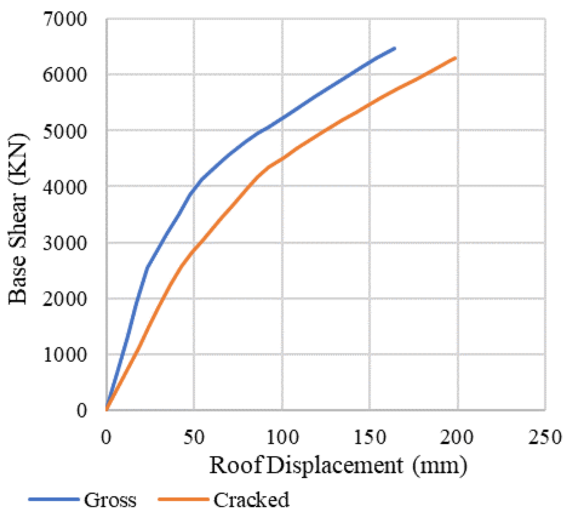

Figure 7: Capacity curve for gross and cracked section models

From the capacity curve, it is quite obvious that the ultimate capacity of the cracked section model is less than the gross section model. The obtained values for ultimate displacement also show the effect of reduced stiffness of the cracked section model. Apart from that, there is a considerable difference in the significant yield point. The building designed using a cracked section seems to absorb the same load through the initiation of global or roof displacement whereas the building designed using gross section resists it by having a higher initial stiffness, which tends to allow less displacement. From the pushover results, it can also be noted that the building designed using gross section overestimates the capacity of the building in terms of base shear.

7. Conclusion

The motive of this research is to evaluate the modeling approach of the buildings in terms of uncracked and cracked stiffness as well as its impact on the structural performance during an earthquake.

From the present study, the following conclusions can be drawn:

- Response of analyzed buildings show that the inter-storey drift and time period have been highly influenced when considering the gross and cracked section respectively.
- The gross section model overestimates ultimate capacity with a considerable margin of safety, which may not represent the real scenario of existing buildings as the cracks occur even due to the service loads.
- Cracked section models dissipate energy through large displacement, but uncracked sections resist it through higher initial stiffness, implying that cracked sections are more flexible as well as ductile.
- The seismic displacement demand for a building designed using cracked section is higher than a building designed using gross section, implying that cracked section modeling is more crucial.

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