Influence of structural cracking in the seismic response of irregular buildings

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Abstract- The authors present an investigation on the influence of cracking as a structural response due to a seismic event. The main objective is to determine the impact that cracking has in the seismic response of irregular buildings, and the importance of including inertia-reducing factors in the design of buildings. First, it is proposed to estimate the inertia-reducing factor of the beams, columns and cracked walls from their moment-curvature diagrams. Once those are determined, a comparative analysis will be performed between the seismic responses of regular and irregular buildings of different heights taking into account their gross and effective rigidity. Subsequently, when analyzing the drifts of the buildings with cracked structural elements, a variation of up to 59% with regard to the non-cracked ones. This is a very high percentage that directly influences the considerations indicated in the designing codes. To summarize, it is of high importance to consider the inertia-reducing factors during the structural design process.

1. Introduction
The fundamental principle of international seismic design codes is based on safeguarding the lives of people and their properties against seismic events. By the same token, urban infrastructure must be protected given that it collapses, daily life and rehabilitation after the earthquake becomes difficult task. However, some of the codes do not consider structural in the calculation of seismic responses, which implies a risk element since cracking can occur throughout the building’s lifetime, or due to low intensity seismic events.

One of the first people who studied the reduction of stiffness as a result of cracking was Fares [1], who proposed experimental results compared to existing methods, which were only analytical. Finally, he obtained that the estimate of the effective stiffness due to the cracks is within an acceptable range. Moreover, Prestley [2] highlights the importance of considering the cracked sections indicating that, through dynamic analysis to the not cracked structure, it is impossible to find precise seismic responses. Specifically, it indicates that the periods and the distribution of forces of the structure are mostly erroneous.

Li and Xiang [3] analyzed the stiffness reduction factors already established in international standards for structures. From this, they concluded that these factor estimates are not appropriate because they are independent of the reinforcement content and axial load to which the structural elements are subjected, and an equation was proposed to estimate more accurately the effective stiffness.

On the other hand, Castel and François [4] studied total stiffness and irreversible deflection in cracked structural elements. It was demonstrated that the reinforced concrete overall behavior during
loading and unloading cycles after cracking represents a significant proportion of the total deflection which the elements were designed for; they also determined that the stiffness of the elements has a progressive decrease according to the cracking level.

In the work carried out by López and Music [5], periods in buildings larger than 10 floors were studied under conditions of cracking and non-cracking in structural walls. The criteria of ACI 318, FEMA 356 and the formula proposed by Paulay and Prestley [6] were used. The results obtained indicate greater displacements between cracked and not cracked buildings in addition to a periods ratio of 1 to 1.5.

Finally, Mohammad Safi and others [7] consider the importance of the effect of cracking in the structural elements, since they directly affect the calculation of natural periods, displacement, among others. For this they used stiffness reduction coefficients proposed in the ACI standard [8] and compared it with the Monte Carlo simulation method. After that, it was shown that the coefficients provided by the standard are not correct since there were variations between 40-55% in the values of displacements and 20-30% in the period.

In the present study, irregular buildings will be analyzed in order to determine the influence of cracking before seismic applications. A reduction factor of the structural elements will be obtained from the moment-curvature graphs to finally make a comparison of the seismic responses between the cases using the effective stiffness and the gross stiffness.

2. Method

This research evaluates the seismic response in irregular structures with different heights, taking into account the variation in stiffness as a result of cracking, which is observable in the moment-curvature relation of each structural element (columns, beams and plates).

Our proposal assumes already built buildings, however, the method to be used can also be applied to buildings in the design phase. The irregularity to be considered is from incoming corners in the plant. To determine the reduction factors, the moment-curvature diagrams will be used considering the amount of steel, the section of the element, and the constitutive relations of the concrete and its reinforcement.

Figure 1 shows the moment-curvature graph with the most important points to carry out the proposed process, which are the moment of creep and the moment of failure of each structural element; these graphs were obtained computationally.

![Figure 1. Bilinear moment-curvature relation](image)

The stiffness evaluation, as is known, from the moment-curvature relation is obtained by:

\[ EI = \frac{M_y}{\varphi_Y} \]  

(1)

Where \( M_y \) is the nominal moment that resists the section of the structural element and \( \varphi_Y \) is the creep curvature.
Applying [6] for the two critical moments obtained from the graph and comparing its slopes, the reduction factor is determined, with which the cracked inertia is found and then perform the dynamic spectral modal seismic analysis of structures. This analysis generates the seismic responses of regular and irregular buildings, which will be evaluated and compared as a final part of the present investigation.

3. Results

For the validation of the study; 3 regular and 3 irregular buildings of 5, 10 and 15 stories high respectively are proposed. Beams, columns and plates are defined as structural elements, where the beams and columns have 210 kg / cm2 as compressive strength and the plates 280 kg / cm2.

The first model (5 floors) has main beams of section (25x40) cm, (25x20) cm in the secondary beams and (25x40) cm in central and eccentric columns. Similarly, in the second and third models (10 and 15 floors) there are main section beams (35x65) cm, secondary beams (30x50) cm, central and eccentric columns (65x65) cm and 30 cm thick plates.

Table 1 shows the factors obtained for the reduction of stiffness for each structural element.

| Element       | Factor |
|---------------|--------|
| 5 Floors      |        |
| Main beam     | 0.511  |
| Secondary Beam| 0.546  |
| Column        | 0.630  |
| 10 Floors     |        |
| Main beam     | 0.589  |
| Secondary Beam| 0.578  |
| Column        | 0.650  |
| Plate         | 0.558  |
| 15 Floors     |        |
| Main beam     | 0.589  |
| Secondary Beam| 0.578  |
| Column        | 0.650  |
| Plate         | 0.558  |

From this, we proceeded to obtain the seismic parameters (periods of vibration, drifts, internal forces) of the 3 buildings considering cracked inertia and gross inertia.

3.1 Periods

The analysis was considered in the first way, since it is where there is greater mass participation. Table 2 shows the periods that exist in each irregular building and how these vary according to their structural cracking and the increase in height of each building.

| Not cracked | Cracked | Variation |
|-------------|---------|-----------|
| 5 Floors    | 1.185   | 1.416     | 19.49%    |
| 10 Floors   | 0.861   | 1.087     | 26.25%    |
| 15 Floors   | 1.303   | 1.619     | 24.25%    |

On average, irregular structures showed a variation due to cracking of 23.33%. On the other hand, to perform the comparison, the analysis was carried out in regular structures, where an average variation of 24.54% was observed. The variation of periods in both regular and irregular buildings, on average, is approximately the same.

3.2 Drifts
When evaluating the drifts, it was considered to maintain the initial basal shear stipulated by the seismic codes, so that this way the structure is subjected to the same force acting on it. With this, through computational methods, the inelastic drifts of the buildings were obtained to proceed with the comparative analysis.

Tables 3 show how much cracking influences when structures undergo an earthquake in the drifts in both directions, demonstrating it by the average variation they represent.

### Table 3. Variation of drifts

|        | Average Variation in Direction X | Average Variation in Direction Y |
|--------|----------------------------------|---------------------------------|
| 5 Floors | 47.21%                           | 59.00%                          |
| 10 Floors | 43.76%                           | 45.10%                          |
| 15 Floors | 24.35%                           | 34.86%                          |

The irregular structures showed an average variation of 38.44% in the X direction, and 46.32% in the Y direction. Also, the procedure was carried out on regular structures, where an average variation of 34.57% was observed in the X direction, and in the Y direction of 31.01%. Therefore, it can be affirmed that is a greater influence of cracking in buildings with irregularities.

#### 3.3 Internal Forces

The internal forces in the buildings were evaluated to propose more real results to design reinforced concrete structures, considering the variations generated in the results due to cracking.

First, table 4 shows the variations of shear forces on average, both in beams and columns in both directions. It was observed that the ranges of variations reach up to 100%.

Secondly, in table 5 the variation that exists of the moments on average is observed, reaching a maximum of 90%. However, it is also observed that there is a negative variation, which is due to the redistribution of the forces.

### Table 4. Variation of shears

| Element  | Direction | Variation |
|----------|-----------|-----------|
|          | X         | 30.00 %   |
|          | Y         | 30.00 %   |
| Beams    | X         | 2.50 %    |
|          | Y         | 5.00 %    |
| 5 Floors | Columns   | 50.00 %   |
|          | Y         | 100.00 %  |
|          | X         | 18.00 %   |
|          | Y         | 60.00 %   |
| 10 Floors| Columns   | 32.00 %   |
|          | Y         | -1.00 %   |
|          | X         | 8.00 %    |
|          | Y         | 55.00 %   |
| 15 Floors| Columns   |           |
|          | Y         |           |
|          | Beams     |           |
Table 5. Variation of moments.

| Element  | Direction | Variation |
|----------|-----------|-----------|
| Columns  | X         | 27.00 %   |
|          | Y         | 27.00 %   |
| Beams    | X         | -5.00 %   |
|          | Y         | 8.00 %    |
| Columns  | X         | 29.00 %   |
|          | Y         | 90.00 %   |
| Beams    | X         | 15.00 %   |
|          | Y         | 50.00 %   |
| Columns  | X         | 2.50 %    |
|          | Y         | 12.00 %   |
| Beams    | X         | 20.00 %   |
|          | Y         | 70.00 %   |

After that, a comparison of the average variations was made with the results obtained in the regular buildings.

Table 6. Comparison of average variations of internal forces in irregular buildings.

| Element  | Direction | Variation |
|----------|-----------|-----------|
| Shears   |           |           |
| Columns  | X         | 37.00 %   |
|          | Y         | 44.00 %   |
| Beams    | X         | 9.50 %    |
|          | Y         | 40.00 %   |
| Moments  |           |           |
| Columns  | X         | 19.50 %   |
|          | Y         | 43.00 %   |
| Beams    | X         | 10.00 %   |
|          | Y         | 42.70 %   |

Table 7. Comparison of average variations of internal forces in regular buildings.

| Element  | Direction | Variation |
|----------|-----------|-----------|
| Shears   |           |           |
| Columns  | X         | 26.50 %   |
|          | Y         | 5.00 %    |
| Beams    | X         | 6.50 %    |
|          | Y         | 70.00 %   |
| Moments  |           |           |
| Columns  | X         | 9.00 %    |
|          | Y         | 11.50 %   |
| Beams    | X         | 45.50 %   |
|          | Y         | 61.90 %   |

Table 6 and 7 show the results obtained where a trend that varies according to the structural element or the internal force analyzed can be observed. Cracking affects more irregular buildings in the case of shear forces, however, in the case of bending moments in beams, it affects more regular buildings.
4. Conclusions
After analyzing the seismic responses of the structures considering the cracking, it has been demonstrated that inertia-reducing factors should be included due to its effects on the design of buildings in order to respond as expected to seismic movements, since drifts increase considerably when cracking is considered. In addition to that, a more conservative design can be obtained if the basal design shear is maintained.

In the same manner, it is observed that the factors of reduction of beams are assimilated to those stipulated by the Complementary Technical Standard of Mexico [9] and the columns and plates resemble the design codes of New Zealand [10], the Complementary Technical Standard of Mexico [9] and the ACI [8]. However, due to the lack of information of some technical standards regarding inertia and cracked stiffness it is recommended to determine the factors taking into account the section, reinforcement, axial load of the element, and its properties.

Finally, if the inertia reduction factors obtained are compared with those recommended by the standards, they are observed to resemble one another. Nonetheless, they are not exactly the same and that is because each designed element is different, so they must have a different factor.

5. References
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