Performance Of Concrete Structure Against Construction Tolerances And Various Kinds Of Imperfections

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ABSTRACT: Growing needs in construction industry has put the performance of concrete structure to perform as intended as a foremost concern. Concrete structure deviate from specifications, quality standards & design plans due to various conditions and challenging circumstances and as a result, as built performance of structure is compromised. Depending upon the type and magnitude of imperfections, accordingly serviceability is affected. However, only those concrete structures which are constructed in accordance with design parameters, specifications and quality control standards, perform satisfactorily. No structure can be constructed with 100% exactness as per drawings and specifications. Actually, during execution phase, accidently, due to lack of competency, lack of engineering knowledge, lack of insight of technical specifications and due to poor workmanship, various kinds of imperfections are resulted which affect the serviceability and performance of concrete structure. Typically, these imperfections include concrete cover, size of structure members, plumb, offset of structural elements, rotation and compressive strength of concrete. The performance of structure has also been evaluated in this work if seismic zone and soil profile has been changed. Construction tolerances provide guidance on various kinds of imperfections parameters and thus define criteria of acceptance. ACI standard 117-90[1] provides guidance and limits on tolerances for concrete construction & materials. In this research, performance and behavior of a typical structure model has been evaluated under various set of imperfections generated and also the tolerances of ACI 117-90[1]. Analysis has been made against UBC defined seismic loadings. It has also been determined which parameters adversely affect the performance and serviceability and which have least damaging impact. In some cases limits of imperfections has also been defined at the point where concrete structure becomes totally unserviceable.
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1. Introduction

Performance, stability and serviceability of structure are significantly affected by the type and magnitude of imperfections. The resultant impact of these imperfections may vary on the scale of structural performance and serviceability depending upon nature of imperfection. The concept of tolerances is gaining popularity and importance in modern construction technology. However, rural construction, commercial and residential construction without deployment of quality assurance and quality control system and lack of inspection, both quality and performance is significantly affected. Therefore in modern construction, tolerances are part of contract specifications books and these are stringently complied.

Tolerances provide permissible limit for acceptance, because perfection in construction is never achieved. By not specifying realistic limit for tolerances may lead to disputes, claims and litigations. Communication among all project teams and high quality project documents are much important and can lead to better and economical results. Realistic values of tolerances should be specified during preparation of working drawings and specifications [4].

Tolerances should be realistic and practical for ease in construction. By specifying closer values of tolerances can lead to excessive cost. Construction tolerances provide us optimum point for construction cost and execution time [5].

Mistakes are inevitable in construction of building. Designer should carefully prepare tolerances in order to avoid problems in construction. He should be responsible for coordination of tolerances, too. Designers design in such a way that errors and mistakes reasonably accommodated without expensive cost and time consuming remedial corrective action on site. Unnecessary and tight limits may lead to excessive rejection work and hence result excessive cost [3].

In developing country like, Pakistan, the quality of the construction is so marginal that it results heavy loss of human assets and economic resources when the structure undergoes repeated cycles of seismic demands. This study particularly highlights construction tolerances, imperfections and its impact of structural performance and safety under earthquake loadings.

2. Methodology

Sate of the art software E-Tab has been used for modeling and structural analysis. Typically five (05) stories model with three bays in both directions have been used. Load combinations defined by UBC-97 section 1612.2 [6] have been used and only seismic analysis was performed for model under consideration.

Following major types of imperfections were considered, one by one, for evaluation of impact on the performance of structure.

1. *Variation in design compressive strength of concrete*
2. *Variation in concrete cover*
3. *Plumpness/eccentricity of columns*
4. *Offset of column*
5. *Offset of beam*
6. *Rotation/orientation of column*
7. *Variation in column cross sectional size*

In addition to above list of imperfections, the impact of following two types of seismic parameters were also evaluated

8. *Change of soil profile types*
9. *Change of seismic zone*

Following basic three (03) types of model were used for analysis:

Model a *Model at service load combination without any kind of imperfection.*

Model b *Model at factored load combination without any kind of imperfection.*

Model c *Model at service load combination with induced imperfection/ACI defined tolerances independently*

There is 100% safety margin without any kind of imperfection in the model, and it drops down accordingly as any kind of imperfection is induced in the model.

The safety margin is calculated as the steel area ratio between model (c) and model (a) to model (b) and model (a). *[(c-a)/ (b-a)] x100%.*

ACI 117-90 [1] also defines limits for construction tolerances. In this research, a comparative line between various types of imperfections and construction tolerances in the forthcoming section are drawn. This study will provide guidance to consultants, constructors, architects, and sponsors on the behavior of structure and degree of acceptance under various types of imperfections.

3. Structural Model

Typically 5 stories model with three (03) bays in both direction have been selected and analyzed using E Tab software as shown in Fig-a and Fig b. For identification of columns, these are numbered from 1 to 6 starting from top to bottom respectively. Structural properties of members and basic model input parameters are shown in Table-1.

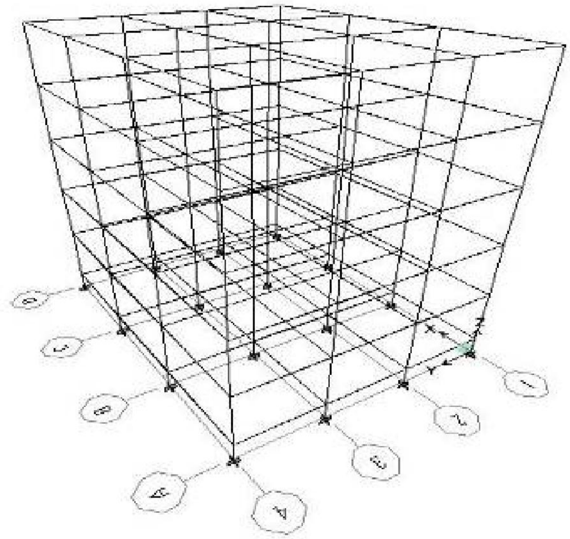

Figure 1: Isometric view of model

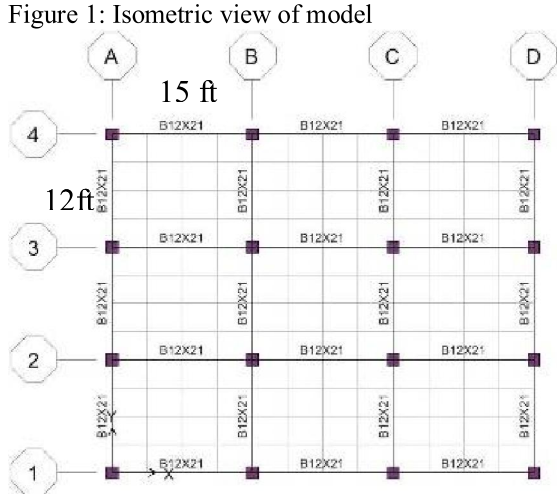

Figure 2: Plan view of model

Table-1: Structural Properties and basic Input parameters

• Sizes of columns	$15'' \times 15''$
• Steel Grade	#60
• Concrete design strength	3000 psi
• Concrete cover	2.5 inch
• Soil profile type	S_C
• Seismic zone	4

3.1 Variation in Concrete Cover

Concrete cover was varied from 2.5” to 3”, 4” and 2” in the model. It has been observed from the analysis results that when magnitude of concrete cover gradually increases then structural performance starts to degrade ACI 117-90 allows only -1/2" tolerance in concrete cover for members sizes over 12" [1]. Against concrete cover 4" and 2" results are plotted in Fig-3.

Against imperfection 4" it has been observed that safety margin has been reduced 38%, 33% and 2 % at location 1/B and 42%, 38% and 28% at location 2/B respectively for columns 4, 5 and 6 as shown in fig-1. Hence, structural performance accordingly is affected.

Concrete cover (2.0") as per ACI specified tolerance limit has negligible effects on structural performance as shown in Fig-3.

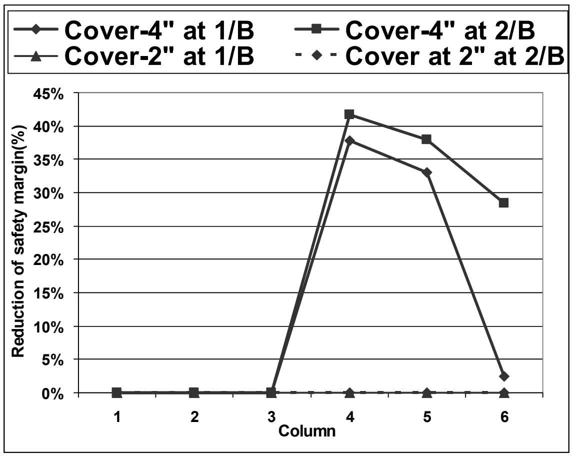

Figure 3: Effect of concrete cover on structure performance

Fig-4 and Fig-5 shows how this imperfection occurs due to poor inspection practices and use of sub-standard form work for structural members in developing countries like Pakistan.


Figure 4: Poor form work and improper concrete cove

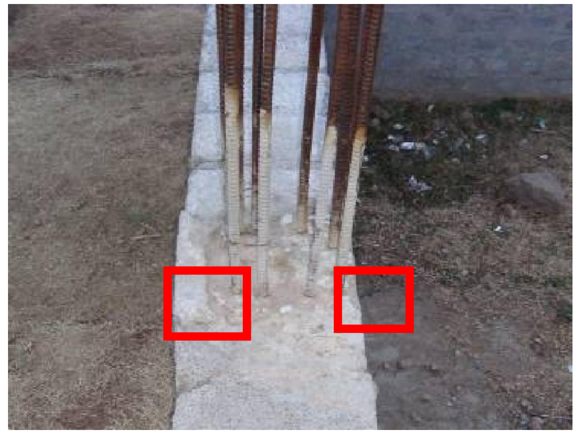
Figure 5: Varying column concrete cover

3.2 Variation in Concrete Compressive strength

Compressive strength of concrete has been varied from design strength of 3000 psi to 2500 psi, 2000 psi and 1500 psi for all columns at locations I/B and 2/B. It has been observed that variation in compressive strength has significant effects on structural performance. ACI 318-05(5.6.3.3) allows 500 psi variation in strength of structural member [2].

Against strengths of 2500 psi and 1500 psi, results are plotted in Fig-2. For strength 1500 psi it has been observed that safety margin has been significantly reduced by magnitude 48%, 55%, 58% and 53 % at location 1/B and 39%, 52%, 49% and 50% at location 2/B respectively for columns 4, 5 and 6 as shown in Fig-6.

When the concrete strength was chosen 2500 psi at location 1/B and 2/B one by one, reduction of safety margin was observed 11%, 13%, and 6% at location 1/B and 16%, 16% and 14% at location 2/B for columns 4, 5 and 6 as shown in Fig-6.

It is clear from Fig-6 that strength 1500 psi has generated adverse effects on structural integrity and has resulted above 50% reduction in available safety cushion.

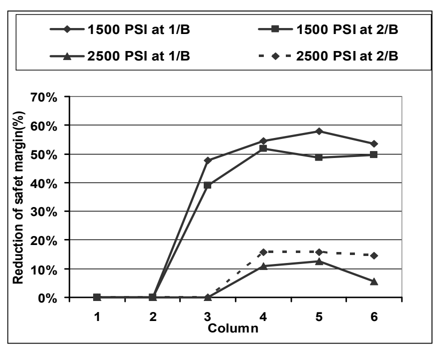

Figure 6: Effect of variation in concrete strength on structure performance

Fig-7 and Fig-8 show the poor quality control on the materials used and poor workmanship of concreting which cause significant variations in the compressive strength of concrete. Fig-7 and Fig-8 show inadequate storage and occurrence of excessive honey combing in developing countries like Pakistan. This can result an adverse effects on structural performance. So measures should be taken to meet design strength.

Figure 7: Poor storage of cement bags

Figure 8: Excessive honey combing in structural column

4 Reduction in cross-sectional dimension of column

Cross section of structural members were varied from designed values of $15'' \times 15''$ to $14.625'' \times 14.625''$, $13'' \times 13''$, $12'' \times 12''$, and $15.5'' \times 15.5''$ for top five columns at locations I/B and 2/B. It has been observed that this imperfection has sizeable effects on the performance of structure. ACI 117-90 allows only -3/8" reduction and +1/2" increment in size of structural member [2].

For sizes $12'' \times 12''$ and $14.625'' \times 14.625''$ results are being plotted in Fig-3 and for $12'' \times 12''$ and $15.5'' \times 15.5''$ in fig-3.1. For size $12'' \times 12''$ it has been observed that safety margin has been significantly reduced by magnitude 9%, 39%, 36% and 0 % at location 1/B and 4%, 34%, 37% and 0% at location 2/B respectively for columns Nos. 3, 4, 5 and 6.

From Fig-9 and Fig-10 it is clear that for member sizes $14.625'' \times 14.625''$ and $15.5'' \times 15.5''$ as per ACI tolerable limits has slight effects on structural safety.

As it is evident from fig-3 and fig 3.1 that reduction in column size from $15'' \times 15''$ to $12'' \times 12''$ has resulted about 40% reduction in safety margin.

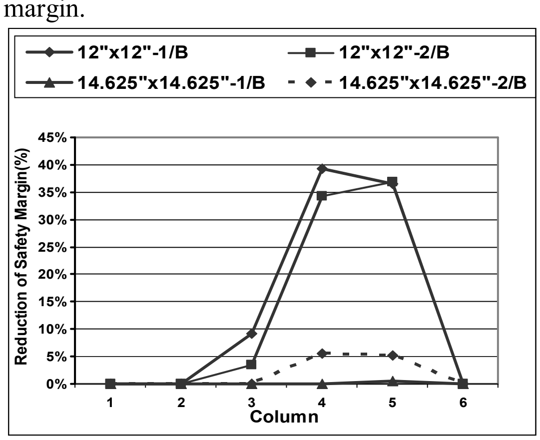

Figure 9: Effect of concrete cover on structure performance

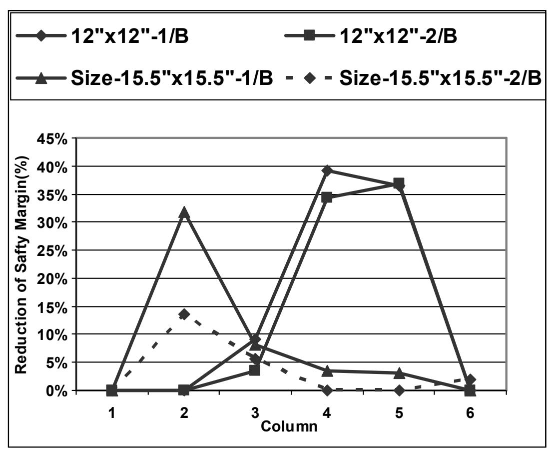

Figure 10: Effect of concrete cover on structure performance

Fig-11 shows how reduction in size of structural members occurs due to poor inspection practices. It is worth noting that what will happen in case of designed seismic activity when the safety is already reduced due to reduction in member sizes because of poor construction.

Figure 11: Varying column cross section

5 Column out of plumb line/ Eccentricity of column

Plumb of columns were changed from 0” to ½”, 1”, 2”, 3”, 4” ,5” and 8” for top five columns at locations I/B and 2/B one by one. It has been observed that this imperfection has negligible effects on the performance of structure hence structure safety is not significantly affected. From aesthetic point of view, plumpness of columns is much critical. Therefore ACI 117-90 allows only 1/2” tolerance for exterior columns and 1” for interior columns [2].

For plumb imperfection of 8” and ½” for column 1/B and for 8” and 1” for 2/B, results are also shown in Fig-12. It has been confirmed from the results that only negligible effects has been observed on the performance of the structure even for sizeable magnitude of imperfections (8”). Against imperfections 8” only 7% reduction in safety margin has been calculated which may be taken as negligible.

For comparison, ACI tolerances of 2% are also plotted in Fig-12.

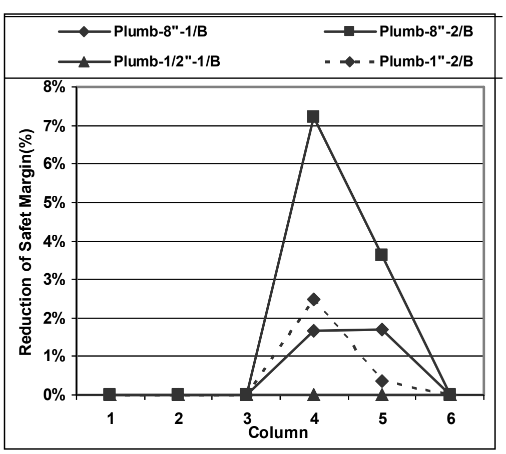

Figure 12: Effect of column plumpness on structure performance

Fig-13 and Fig-14 demonstrates how out of plumb of columns occur in structure due to poor workmanship and lack of proper inspection in developing. Straightness of structure is much critical from aesthetic consideration and that is why ACI has imposed stringent values on tolerances.

Figure 13: Plumness of column

Figure 14: View of column out of plumb

6 Offset of column

At locations 1/B and 2/B, top five columns were given offset 1”, 1.5”, 2”, 2.5” and 3” one by one. Results form Fig 15 confirms that this imperfection has slight effects on structural performance. ACI 117-90 allows 1” tolerance for both exterior and interior columns [2].

Against imperfection parameters 3” and 1” results are plotted in Fig 15. It is clear from Fig 5 that for offset 3” in column, maximum 20% reduction in safety margin has been observed.

ACI allowable limit 1” has negligible effects (4%) on structural safety margin which is also plotted in Fig-15 for reference.

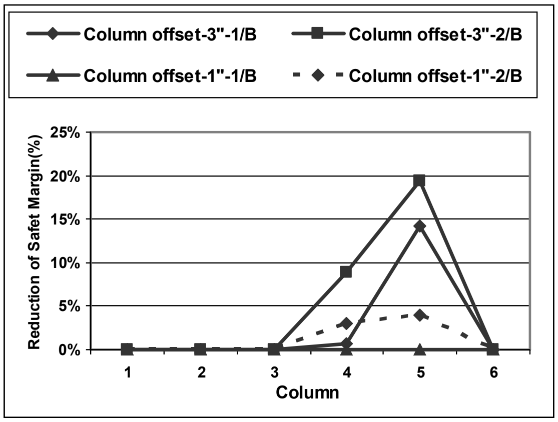

Figure 15: Effect of column offset on structure performance

Fig-16 and Fig-17shows how deviations in lateral alignment of structure occurs due to inadequate layout practices and lack of proper inspection practices in developing countries like Pakistan.

Figure 16: Column off set view

Figure 17: Offset of column

7 Offset of Beam/Lateral Alignment of beam

Lateral alignment of beams was changed from 0” to 0.5”, 1”, and 1.5” at location ABCD/1 first floor. Results confirm that negligible effects on structure safety has been observed. ACI 117-90 allows 1” tolerance for lateral alignment of members [2].

For lateral alignment imperfections of 1.5” and 1”, even less than 1% reduction in safety margin has been observed. Thus from ACI allowable limit of 1” has also negligible effects on structural safety. Since for the set of imperfections in lateral alignment of beams has negligible effects on structure safety, therefore, results are not plotted here

.Fig-18and Fig-19 are a few examples of imperfections in lateral alignment of beams in real construction in Pakistan.

Figure 18: Offset of beam

Figure 19: Offset of Beam

8 Orientation/Rotation of Column axis

At location 1/B and 2/B, top five columns were rotated from 0 degree to 5 degree, 10 degree, 15 degree, and 20 degree. Results confirm that slight effects on structure safety has been observed. ACI code does not give any guidance for this type of imperfection. This imperfection is much critical aesthetically. However, if the magnitude of this imperfection increases, aesthetic of the structure is affected accordingly.

Against rotation 20 degree, maximum 8% reduction in safety margin has been observed as shown in Fig 20.

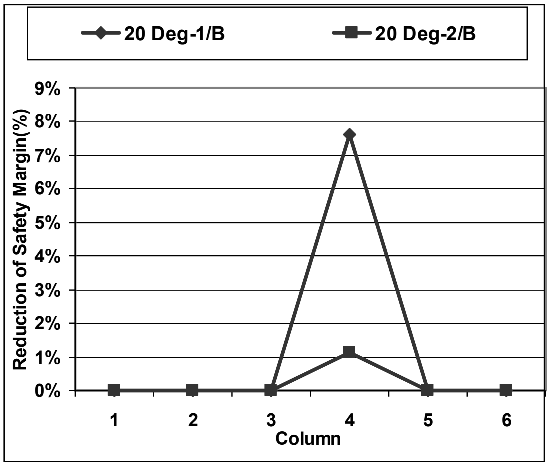

Fig 20: Effect of column rotation on structure performance

Figure 21: shows a practical example of column rotation in column axis.

9 Variation in Soil Profile Types

Soil properties vary from one location to another location. Therefore soil investigation is carried out for determining engineering properties of the soil of the specified location. Designer takes bearing capacity and soil type etc as inputs data for designing purpose of concrete structure. Incorrect soil parameters may lead to heavy loss to property as well as the serviceability of the structure is severally impaired. Sometimes it may happen that without determining soil properties of specified location, either soil parameters are assumed or same values are taken as of already soil investigation conducted of nearby location for design purposes. This methodology apparently does not seem most critical but actually later on causes irreparable damage to human lives as well as valuable properties.

Soil profile was changed from S_C to S_D for all structural components of model under consideration. Result reveals that this variation from S_C to S_D has resulted in considerable reduction in magnitude of safety margin.

The results are plotted in Fig-22 below for specific columns 1/B and 2/B and have noted that safety margin has been reduced considerably by 58%, 59% and 28% at location 1/B and 60%, 46% and 41% at location 2/B for columns 4, 5 and 6. Therefore, 50% safety of the structure is compromised based on only change in soil profile. Therefore proper soil investigation should is of prime importance for the sustainability of structure otherwise will damage the performance of the structure.

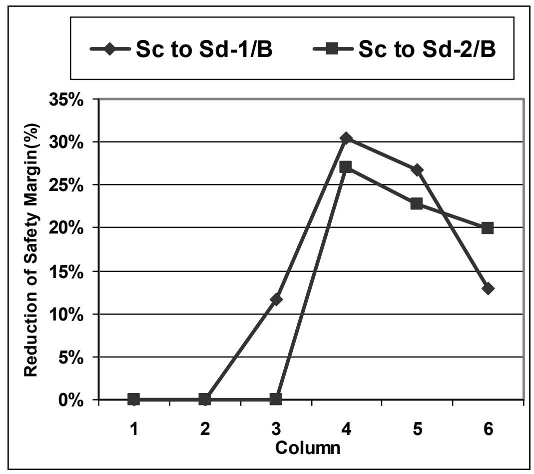

Fig 22: Effect of variation in soil profile types on structure performance

10 Change of Seismic Zone

Intensity of earthquake change from zone to zone and accordingly the performance of structure are affected. Each country has a specific seismic map and different seismic zones are marked on it. Research shows that structures totally collapse in performance if they are designed against low intensity seismic zone and actually constructed in higher intensity seismic zone with the same detailing of low intensity seismic zone.

Some times designer or client only for the sake of economy, designs for low seismic zone and are actually placed in high seismic zone. They may lead to catastrophic potential impacts during earthquake.
The structure performance is analyzed for variation in seismic zone. Seismic zone was changed from 3 to 4 and the results were compiled. Results show that this change in seismic zone has resulted in catastrophic reduction of safety margin and whole structure has failed in performance as shown in Fig 9.

Research results are shown in Fig-23 for typical columns at locations 1/B and 2/B respectively. It is clear from the research analysis that safety margin for all structure members have drastically been reduced due to this change in seismic zone and structure has been failed in performance. So building should be strictly designed and constructed as per seismic zone category. Misconception about seismic zone may result in heavy damages to both human assets and capitals.

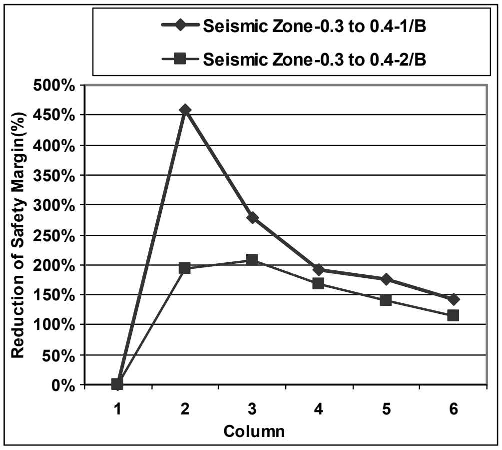

Fig 23: Effect of Seismic zone on structure performance

11 **Conclusions And Recommendations:**

1. Performance of a structure is significantly affected by the type of imperfection, its magnitude and configuration of structural member.
2. Perimeter columns undergo more severe impact as compared to interior columns.
3. Rotation of column and offset of beam has negligible effect on structural performance.
4. Compressive strength, reduction in cross sectional dimensional of columns and concrete cover have significant impact on safety margin and serviceability of structure.
5. Seismic zone and soil profile types is of great importance for seismic performance of structure. Ignorance on these parameters may result in catastrophic failure resulting in heavy loss to human life and property.

It has been noted that ACI 117-90 tolerance limits are much conservative. It also does not address limit for rotation of column axis.

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