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# RESPONSE SPECTRUM ANALYSIS AND DESIGN OF CASE STUDY BUILDING

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## ABSTRACT

*The use of fragility curves for the assessment of seismic losses is in increasing demand, both for pre-earthquake disaster planning as well as post-earthquake recovery and retrofitting programs. Fragility curves; important components of accurate risk assessment are functions that describe the probability of failure, conditioned on the full range of loads to which a system might be exposed. In general fragility curves provide estimates for the probabilities of a structure reaching/exceeding limiting deformation at given levels of ground shaking or it is a plot of the computed probability (deflection) Vs. Ground motion parameter. The scope of the proposed research is to develop fragility curves as a tool to develop suitable measures that can help in estimating the losses for the structures, which are similar to the case study building and thus to develop the same as an important tool in earthquake engineering mainly for urban risk reduction. The objective of the proposed study is the reliability assessment of the case study building to earthquake loadings through the development of fragility curves. The vulnerability of the structure is expressed with the development of fragility curves, which provides the probability of exceeding a prescribed level of damage for a wide range of ground motion intensities. Primary task is to identify a case study structure for which fragility curves are not developed yet and which could effectively represent the structural viability of present and future buildings. It is based on a concept that similar type of structures (structural typology) will have same probability of a given damage state for given earthquake intensity. Hence effective methods to develop fragility curves for representative buildings are very vital in earthquake engineering. It is proposed to develop fragility curves for a building with flat-slabs and shear wall system which effectively represents recent high rise buildings particularly in GCC countries. This paper presents the work done till date for the development of fragility curves for vulnerability analysis of the case study*

*building. Selection of case study building, its response spectrum analysis and design of the full structure is presented here.*

**Key words:** Earthquake Engineering, Reliability Analysis, Earthquake Engineering, Fragility Curves, Shear Wall System, Flat Slab Structures.

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## 1. INTRODUCTION

### 1.1. Background

Earth and its environment have become increasingly vulnerable to natural hazards. This being the situation, it is quite important to adopt proper assessment methods, planning and design techniques to prevent the effect of natural hazards like earthquake, wind etc. into extreme disasters. Lack of proper planning and ill-engineered construction are the main causes which increases the risk of natural hazards. In this scenario, vulnerability assessments play a major role in the design, construction and maintenance of structures. Earthquake vulnerability studies/assessment, when properly integrated with engineering measures helps to minimize building/infrastructure damages.

### 1.2. Performance Based Engineering

Performance-based design is a more general design philosophy in which the design criteria are expressed in terms of achieving stated performance objectives when the structure is subjected to stated levels of seismic hazard. The performance targets may be a level of stress not to be exceeded, a load, a displacement, a limit state or a target damage state. Performance based engineering implies a shift away from the dependence of empirical and experience based conventions and towards a design and assessment process more firmly rooted in the realistic prediction of structural behavior under a realistic description of spectrum of loading environment that the structure will experience in future. It allows for selection of a specific performance objective based on various parameters, including the owner's requirements, the functional utility of the structure, the seismic risk and potential economic losses. In spite of these advances, many structures in the GCC countries and around the world were not designed for any level of seismic resistance.

### 1.3. Earthquake Vulnerability Analysis

Another important field of study in earthquake engineering is vulnerability analysis. It is a relatively new research area which needs more input from the researchers. Initiatives such as Hazard United States (HAZUS) have made a substantial start on assessment of vulnerability, using the predicted ground-motion spectrum to estimate the amount of damage that is likely to be inflicted on buildings of known design in a given earthquake scenario. While hazard assessment combines source and attenuation modelling, vulnerability analysis goes one step further, to estimate likely losses to structures by modelling their vulnerability. This results in probabilistic estimates of losses for specific portfolios of assets. Seismology has traditionally been close to the engineering profession, and this has resulted in the development of procedures for earthquake hazard assessment that are useful for engineering design. The advantage of vulnerability assessment is that it can be accurately used to predict damages/losses to buildings owing to earthquake and so can be effectively linked to risk management sectors.

### 1.4. Fragility Curves

Fragility curves are functions that describe the probability of failure, conditioned on the full range of loads to which a system might be exposed. In general fragility curves provide estimates for the probabilities of a population of structures reaching/ exceeding limiting deformation at given levels of ground shaking or it can be defined as a plot of the computed probability (deflection) Vs. Ground motion parameter. The data derived from fragility curves can be used to analyse, evaluate and improve the seismic performance of both non-structural and structural elements.

Fragility curve is an effective tool for vulnerability assessment of structural systems. The fragility curve, which is developed from the behaviour model of structure, capacity and a suite of ground motions, is a graphical representation of the seismic vulnerability of a structure.

## 2. RESEARCH GAP IDENTIFIED

It is to be noted that high rise buildings with shear walls is the most common type of buildings in GCC area. Owing this, a case study building is selected, which is a high rise building with height of about 78m in which shear walls in orthogonal direction serve as the lateral load resisting system. For the selected case study building fragility curves are not developed and this building effectively represents the structural viability of present and future buildings.

## 3. SCOPE AND OBJECTIVE

The scope of this research is to develop fragility curves that can help in estimating the damages in the present and future earthquakes for the structures similar to the case study building.

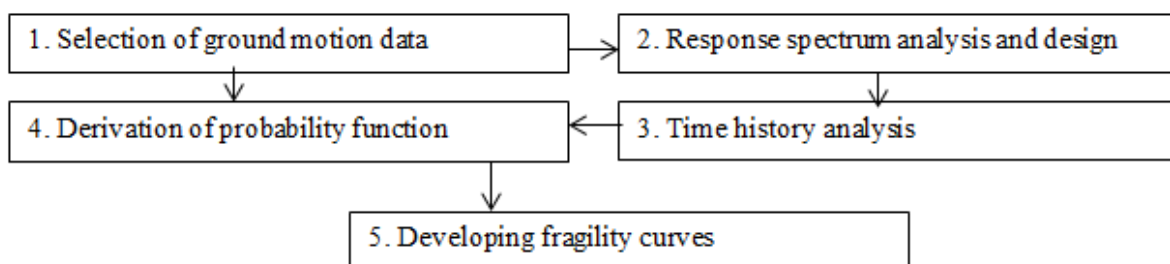
The objective of this study is the reliability assessment of high rise buildings with shear walls subjected to earthquake loading. The vulnerabilities of these structures are to be expressed with the development of fragility curves, which provide the probability of exceeding a prescribed level of damage for a wide range of ground motion intensities.

By developing fragility curves, links of earthquake intensity to the probability of exceeding specific performance levels for the structure and the improvement in seismic performance can be evaluated.

## 4. METHODOLOGY

Development of fragility curves for the case study building involves a step by step methodology. Based on the studies conducted so far, following methodology is proposed.

**Table 1** Proposed Methodology



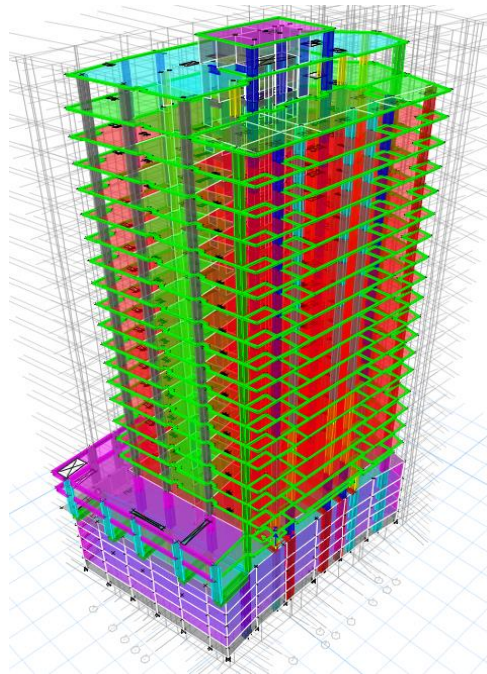
As part of the research work and based on the above given methodology, Steps 1 and 2 are finished until date. This paper summarizes the work done under Step 1 and 2.

## 5. CASE STUDY BUILDING

Primary task was to identify a case study building. Building was chosen taking into account the fact that, no fragility curves were developed before for the same and it effectively represents the structural viability. Basic concept for selecting the case study building is that similar type of structures have same probability for a given damage state for given earthquake intensity.

As part of the research a Case Study building is chosen - A proposed high rise building in Abu Dhabi, United Arab Emirates. It is identified as a typical high rise building in the region with shear walls as the basic lateral load resisting system.

The project consists of (5B+G+2Podiums+17) with a total area of 28345 m<sup>2</sup>. Approximate building height is 78m (excluding basement).



**Figure 1** ETABS – 3D Model of the Case Study Building

### 5.1. Superstructure

The superstructure (here defined as “above raft”) is designed as a RC structure. Walls, columns beams and slabs are constructed as conventional, cast in-situ RC.

### 5.2. Gravity System

The typical floors are RC slabs (approximately 240mm thick with local thickening of 280mm) which rest on RC columns and walls. Stair flights are designed as in-situ RC (approximately 175mm thick).

The figure below shows the slab layout at typical floor level:

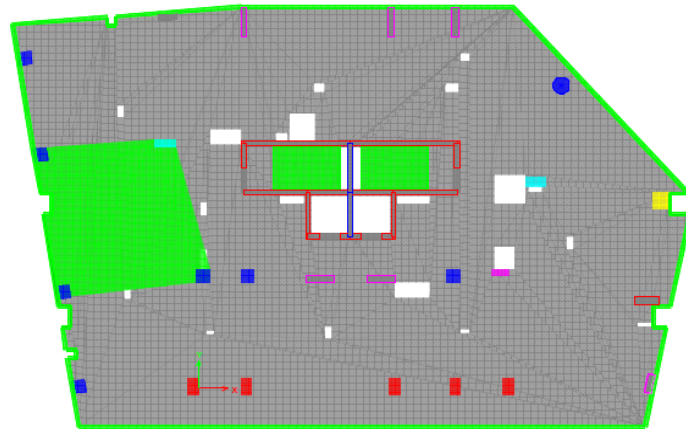


Figure 2 Typical floor level: Slab layout

The basement floors are RC slabs (approximately 250mm with column drops of additional 100mm thickness where required) which rest on RC columns and walls.

### 5.3. Lateral system

The lateral load resisting system consists of shear walls and columns in both orthogonal directions, which can be classified as a building frame system. The lateral load is transferred to the shear walls by means of a horizontal diaphragm, i.e. the floor slabs.

The thickness of the walls is of the order of 300 to 600mm, whereas the core walls in the basement levels are in the range of 300 to 400mm. The figures below show the lateral load resisting system at typical floor levels:

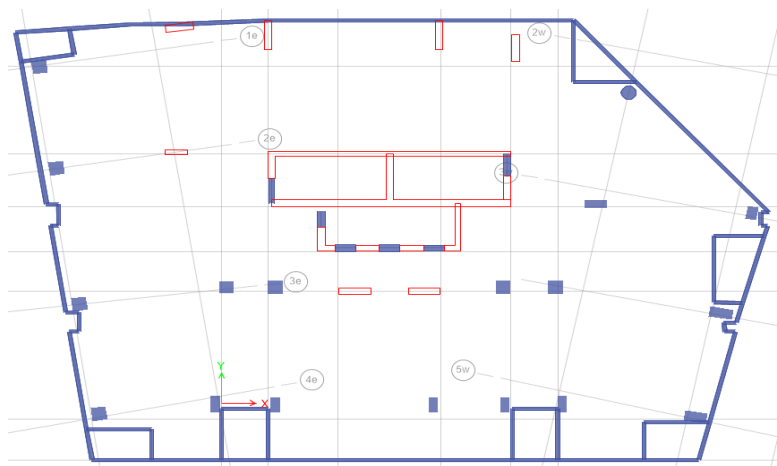


Figure 3 Lateral Load Resisting System in Typical Floor

### 5.4. Foundation System

The structure rests on a raft foundation, which is complemented by a number of tension piles below the podium area to resist the water uplift.

## 6. DETAILS OF ANALYSIS

### 6.1. Second Order Analysis (P - Δ)

A second order analysis with the following load factors is included in the design:

$$1.2D + 0.5L$$

## 6.2. Construction Sequence Analysis

Relevant elements such as the transfer beams and its supporting columns are analyzed for construction sequence of above elements with following loads: 1.0D + 1.0SDL

## 6.3. Stiffness Modifiers

The following stiffness modifiers are used based on ACI 318 10.10.4.1:

**Table 2** Stiffness Modifiers

Element	ULS	SLS
Columns	0.7	1.0
Walls (uncracked)	0.7	1.0
Beams	0.35	0.5
Slabs	0.25	0.35

## 6.4. Floor Diaphragm

The floor slabs are modelled as a semi-rigid diaphragms in accordance with ASCE 7 (05) 12.3

## 6.5. Wind Load

As per ASCE 7 (05), the following wind load is used:

- Wind speed,  $v_b$  = 38 m/s
- Terrain exposure type "B"
- Importance factor, I = 1.0
- Directionality factor,  $k_d$  = 0.85
- Gust factor, G = 0.85
- Pressure coefficient,  $C_p$  = +0.8 / -0.5 (windward / leeward wall)

Based on the above parameters, the following design wind pressure for enclosed and partially enclosed buildings is used in design:

$$\text{Velocity pressure, } q = 0.613 * K_z * K_{zt} * K_d * V^2$$

Wind load is applied as per the 'all heights method' of ASCE 7 (05), i.e. for cases 1 to 4 figure 6-9

## 6.6. Seismic Load

As per [IBC 2009], the following seismic load is used:

- Soil  $S_c$
- Mapped spectral acceleration,  $S_s$  = 0.6
- Mapped spectral acceleration,  $S_1$  = 0.18
- Site coefficient,  $F_a$  = 1.165
- Site coefficient,  $F_v$  = 1.620

Adjusted MCE spectral response,

$$SMS = S_s * F_a = 0.60 * 1.165 * V^2 = 0.699$$

$$SM1 = S1 * F_v = 0.18 * 1.620 = 0.291$$

Hence, structure is to be designed as per design category C. For a building frame, the following design parameters are applicable:

Response modification factor, R = 5.0

Over-strength factor,  $\Omega$  = 2.5

(Applicable to transfer slabs and walls / columns which carry a discontinuous vertical system)

Deflection amplification factor, Cd = 4.5

Redundancy factor,  $\rho$  = 1.0

Seismic loads are considered in the model for both, equivalent static method as well as response spectrum method. For design of vertical elements, forces from response spectrum method are considered.

### 6.7. Vertical Irregularity

The current arrangement of the lateral load resisting system does not classify as a vertical irregularity.

### 6.8. Horizontal Irregularity

Horizontal irregularities are checked and appropriate parameters are applied to the design models if such irregularities are found in the design process. For example:

As per [ASCE 7-05] 12.5.3, orthogonal seismic loads are combined by means of the 100/30 rule.

As per [ASCE 7-05] 12.8.4.3, accidental torsional moments are amplified if  $d_{max} > 1.2 * d_{avg}$  by the following factor:

$$\text{Amplification factor } A_x = (d_{max} / 1.2 * d_{avg})^2 \leq 3.0$$

### 6.9. Load Combinations

Load Combinations are as per IBC 2009 and ASCE 7-05, with the vertical combination of the seismic load taken as the unfavorable of

$$\text{IBC (ULS): } 0.20 * SDS = 0.09$$

Wind and earthquake loads shall not be assumed to act concurrently.

## 7. SERVICEABILITY CHECKS

### 7.1. Horizontal Deflection (drift)

The following drift limits have been considered:

Seismic  $0.02 * h$

Wind  $h/400$  to  $600$

Refer to [ASCE 7-05] Appendix C

Tower height above ground, H =79m

Estimated deflection in x-direction,  $w_x$  =31.7mm

Results in a drift ratio of H/2492

Estimated deflection in y-direction,  $w_y$  =89mm

Results in a drift ratio of H/888

The wind drift ratios of the tower are well below the limit of H/400 to H/600 and hence acceptable. This remains valid even if the lateral load resisting system experiences moderate cracking and hence the stiffness would reduce.

## 7.2. Vertical Deflection

The following deflection limits have been considered in accordance to [ACI 318-05] for all slabs and beams:

**Table 3** Deflection Limits

Load	Element	Criteria	Limit
4.0D + 4.0SDL + 1.5L	slabs / beams	long term deflection	span/240 <sup>\$</sup>
L	slabs / beams	immediate deflection	span/360

## 8. DESIGN DETAILS

Response Spectrum Analysis of the building is carried out. Seismic loads are considered in the model for both, equivalent static method as well as response spectrum method. For design of vertical elements, forces from response spectrum method are considered.

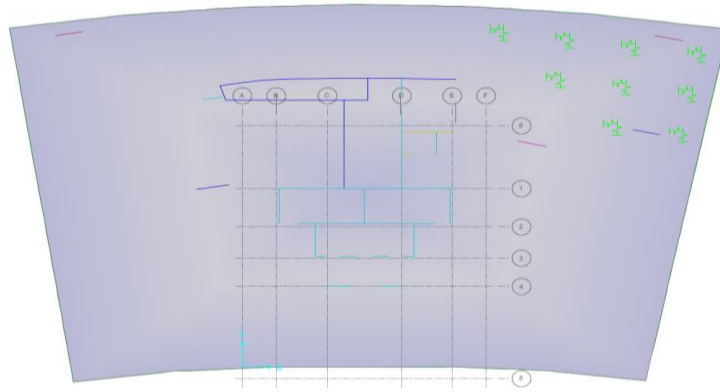
Full structural design of the building including all structural elements slabs, beams, columns, walls, raft foundation, tension piles and staircase is finished.

### 8.1. Raft Design

The raft is modelled with shell elements, supported on a modulus of subgrade reaction with a stiffness of 37,200kN/m<sup>3</sup> as given in soil report and piles with an assumed vertical stiffness of 2607kN/mm.

The raft is designed with a general thickness of 1.5m (purple in the figure above). In a first step, results of all load cases are evaluated after a linear analysis before load cases with significant tension between the soil and the raft have been converted to non-linear cases in order to eliminate the tension at this interface. Uplift forces on the raft due to hydro-static pressures require the use of tension piles at certain locations.



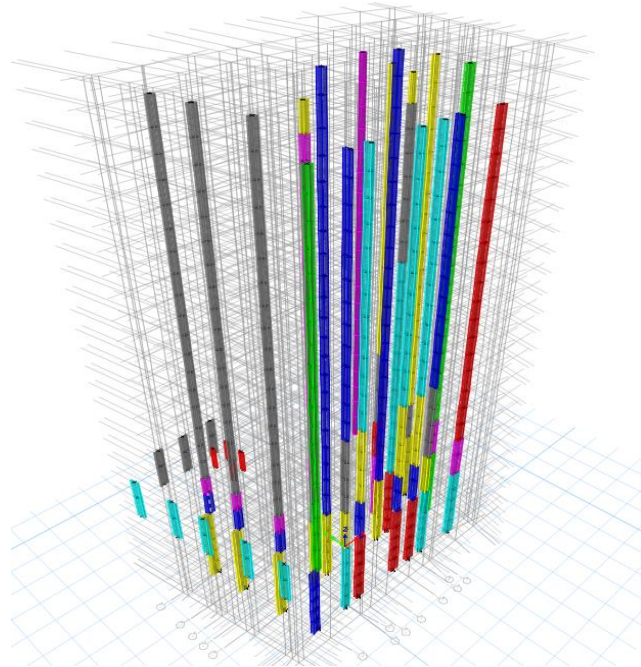


**Figure 4** Raft layout with tension piles

## 8.2. Column Design

Due to the presence of shear walls all concrete columns are designed as non-sway columns assuming sufficient lateral restraint columns with appropriate modification factors. Appropriate modification factors as mentioned in Table 2 are applied on columns.

Design of columns is carried out in ETABS ensuring minimum reinforcement percentage of 1.



**Figure 5** Columns designed in ETABS

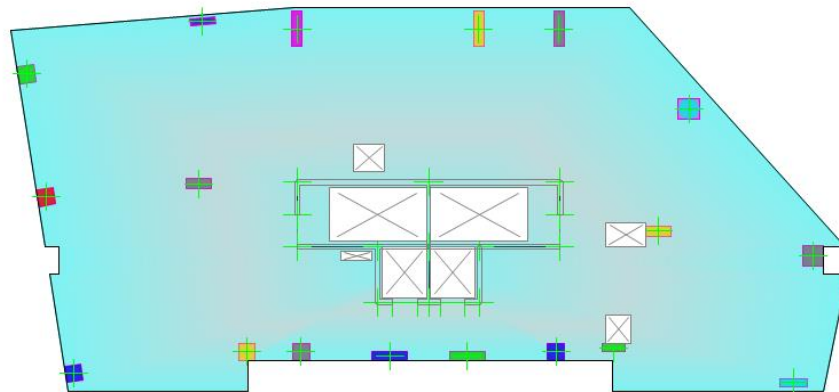
## 8.3. Slab Design

Each floor slab is modelled in SAFE 2014. Design of slab is based on load combo corresponding to  $1.2D + 1.2SDL + 1.6L$ .

Long term deflection analysis of slabs is carried out based on two approaches.

- ACI 318
- Conventional approach

The value of effective modulus of rupture is assumed as 2.87MPa for long term crack analysis of slabs based on ACI 318. For conventional approach, load combo corresponding to  $4.0D + 4.0SDL + 1.5L$  is considered.



**Figure 6** Upper Floor Slab in SAFE

Slabs are 250-300mm thick with mostly a reinforcement mesh of T12@200 top and bottom. In addition to this, additional reinforcement is provided at both top and bottom of the slab. Punching shear reinforcement is provided when the shear coefficient is more than 0.9. Local thickening is also considered.

#### **8.4. Beam Design**

Structural design of beams is carried out in ETABS. Minimum reinforcement requirements are also taken into account. Structural design is carried out to keep within the original architectural and MEP design. Ultimate stress checks and serviceability checks including deflection checks are also carried out. In some locations in Ground floor there is vertical discontinuity of columns. In this area columns are supported on transfer beams of 1.35m depth. For all transfer beams and its supporting columns, construction sequence analysis is performed. Also design is executed for increased seismic load.

### **9. CONCLUSIONS**

Seismic loads are considered in the model for both, equivalent static method as well as response spectrum method.

As the considered case study building falls under the category of tall and irregular building, the fundamental mode of vibration is not dominating the response. Hence dynamic analysis using Response Spectrum method is adopted. Modal analysis is performed to compute modal responses and they are combined using SRSS method to get the maximum responses. For design of vertical elements (columns and shear walls), forces from response spectrum method are considered. For the design of foundation worst load combinations of earthquake forces as well as uplift water pressures are considered.

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