STRUCTURAL DESIGN CRITERIA FOR TYPE DESIGN OF SCHOOL BUILDINGS

This document presents the proposed design criteria and overall methodology to be used for the structural design of school buildings. This document will be considered as an Interim Guidelines, until the NBC is revised or additional hazard mapping and assessment is available.

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This document has been prepared by the Asian Development Bank (ADB) and Japan International Cooperation Agency (JICA).

The document is intended to be the official guidelines to the Department of Education (DOE), for structural aspects of planning and design of new schools consistent with the Design Guidelines for Type Design of School Buildings which sets out architectural and planning requirements.

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List of Abbreviations

ACI	American Concrete Institute
ADB	Asian Development Bank
ASCE	American Society of Civil Engineers
DBE	Design Basis Earthquake
DOE	Department of Education
DUDBC	Department of Urban Development and Building Construction
GON	Government of Nepal
IBC	International Building Codes
IS	Indian Standard
MCE	Maximum Considered Earthquake
NBC	Nepal National Building Code
NEHRP	National Earthquake Hazards Reduction Program
NIST	National Institute of Standards and Technology
NLTHA	Nonlinear Time History Analysis
PDNA	Post Disaster Needs Assessments
PEER	Pacific Earthquake Engineering Research Center
PGMD	PEER Ground Motion Database
RC	Reinforced Concrete
RS	Response Spectrum Analysis
UBC	Uniform Building Code

Chapter 1 Introduction

1.1 Introduction

A major earthquake of shallow depth measuring 7.6 on the Richter scale struck central Nepal on April 25th causing widespread destruction. There have been several aftershocks, including a big one measuring 6.8 on May 12 causing further causalities and damage

The Government of Nepal (GON), and several development partners have developed a comprehensive Post Disaster Need Assessment (PDNA) document. One of the sector considered in the overall PDNA is Education, which identities the needs for rehabilitation and reconstruction of effected infrastructure for education sector, including the school buildings and facilities. A draft strategy was prepared for reconstruction after this disaster, addressing both short term and long-term reconstruction, in line with the overall framework of “Build Back Better”.

As part of the rebuilding strategy, guidelines have been developed for the design of new schools[1] . This document is developed to support the structural design of the school buildings to be designed based on the guidelines. It is important to carry out proper structural design of the type design for various hazards, as well as for cost effectiveness.

This document presents the design criteria and overall methodology to be used in the structural design of new school buildings in Nepal. The criteria presented includes specific information on the description of the building and its structural system, codes, standards and references, loading criteria, materials, modeling, and the proposed analysis and design procedures. This document will be considered as an Interim Guidelines, until the NBC is revised or additional hazard mapping and assessment is available.

1.2 Scope and Purpose

This document is intended to provide a unified and consistent criterion for carrying out detailed structural design of school buildings in Nepal, for resistance to the effects of earthquakes and other natural hazards. The document is particularly applicable to the Type Design of new school buildings for the post-earthquake reconstruction in the 14 most effected districts.

However, the document may also be used for structural design of school buildings in general in the entire country once approved and adopted by the Department of Education in consultation with and agreement of DUDBC. School buildings covered by the document may be single or multi-story buildings [2]. The buildings may be located anywhere in Nepal, either in mountains, hills or plains.

1.3 Structural System

Five types of basic structural systems considered in this document with an objective to achieve the good performance and cost effectiveness. The structural systems to be developed are as below.

1) ***Sys-1:*** Ordinary reinforced concrete moment frame with unreinforced masonry infill walls
2) ***Sys-2:*** Special steel moment resisting frame

[1] Guidelines for Developing Type Designs for School Buildings in Nepal, February 2016.

[2] For all type design, it should be approved by DOE and DUDBC, and also meet code provisions like fire exit and lift.

3) ***Sys-3:*** Reinforced interlocking block bearing wall system (for example, Habitech system)
4) ***Sys-4:*** Special reinforced concrete moment frame
5) ***Sys-5:*** Cold-formed steel ordinary moment frame
6) ***Sys***-6: Hold-rolled steel ordinary moment frame
7) ***Sys***-7: Timber structure

Isolated and strip footings may be used to transfer the load of the building to supporting soil, depending on the soil conditions at site. Steel truss or RC slab may be used to support the roof system, whereas intermediate floors may either be of RC slab on RC frame or composite slab on steel frame.

1.4 Structural Components

The components of structural systems are summarized in the following table.

Table 1-1 : Typical Structural Member and Components

Structural System	Element	Typical Component Types
Sys-1: Ordinary RC moment frame with masonry infill walls	Foundation	RC isolated footing for column or RC strip footing for column and wall
	Column	RC column
	Masonry wall	Burnt-brick in c/s mortar (1:6), tied to RC frame
	Beam	RC beam
	Slab on grade	Generally not required
	Plinth beams	RC beam
	Lintels	RC beam
	Intermediate floors	RC slab
	Walls	Unreinforced masonry walls full contact with bounding frames
	Roof system	Steel truss or RC slab
Sys-2: Special steel moment resisting frame	Foundation	RC isolated footing for column RC strip footing for column
	Column	Steel hollow box or H, I or W shapes, or built up sections
	Beam	Steel hollow box or I sections, or built up sections
	Slab on grade	Generally not required
	Plinth beams	RC beam
	Lintels	RC beam
	Intermediate floors	Composite slab
	Walls	Unreinforced masonry walls, Light weight partitions (non-load bearing walls)
	Roof system	Steel truss or composite slab
Sys-3: Reinforced interlocking bearing wall (Habitech system)	Foundation	Brick or stone RC strip footing for wall reinforced stone masonry in C/C mortar
	Bearing wall	Compressed interlocking blocks, reinforced with rebars

Structural System	Element	Typical Component Types
	Slab on grade	Generally not required
	Plinth beams	RC beam, blocks reinforced with rebars
	Lintels	RC beam, blocks reinforced with rebars
	Intermediate floors	RC slab, Habitech waist slab or similar
	Roof system	Steel truss or RC slab
Sys-4: Special reinforced concrete moment frame	Foundation	RC isolated footing for column RC strip footing for column
	Column	RC column
	Beam	RC beam
	Slab on grade	Generally not required
	Plinth beams	RC beam
	Lintels	RC beam
	Intermediate floors	RC slab
	Walls	Unreinforced masonry walls, Light weight partitions (non-load bearing walls)
	Roof system	Steel truss or RC slab
Sys-5: Cold-formed steel ordinary moment frame	Foundation	RC isolated footing for column RC strip footing for column
	Column	Cold-formed channel sections
	Beam	Cold-formed channel sections
	Slab on grade	Generally not required
	Plinth beams	RC beam
	Lintels	RC beam
	Intermediate floors	Not permitted.
	Walls	Unreinforced masonry walls, Light weight partitions (non-load bearing walls)
	Roof system	Cold-formed steel channel truss
Sys-6: Hot-rolled steel ordinary moment frame	Foundation	RC isolated footing for column RC strip footing for column
	Column	Steel hollow box or H, I or W shapes sections
	Beam	Steel hollow box or I sections
	Slab on grade	Generally not required
	Plinth beams	RC beam
	Lintels	RC beam
	Intermediate floors	Composite slab
	Walls	Unreinforced masonry walls, Light weight partitions (non-load bearing walls)
	Roof system	Steel truss or composite slab
Sys-7: Timber structure	Foundation	RC isolated footing for column RC strip footing for column
	Column	Timber column
	Beam	Timber beam

Structural System	Element	Typical Component Types
	Slab on grade	Generally not required
	Plinth beams	RC beam
	Intermediate floors	Timber floor
	Roof system	Timber truss

1.5 Codes, Standards and References

The basic building codes to be referred are listed below. However, specific applications of those code provisions are discussed in the corresponding sections.

Building Codes

- Seismic Design of Buildings in Nepal, Nepal National Building Code, NBC 105: 1994, or later editions, as applicable
- Wind Load, Nepal National Building Code, NBC 104: 1994, or later editions, as applicable
- Criteria for Earthquake Resistant Design of Structures, Indian Standard, IS:1893 (Part 1) - 2002
- International Building Code, IBC 2012, International Code Council, Inc.
- Uniform Building Code, UBC 97, International Code Council, Inc.

Material Codes

- Steel: Nepal National Building Code, NBC 111: 1994, or equivalent
- Plain and Reinforced Concrete: Nepal National Building Code, NBC 110: 1994, or equivalent
- Masonry: Unreinforced: Nepal National Building Code, NBC 109: 1994, or equivalent
- Mandatory Rules of Thumb Concrete Buildings with Masonry Infill, Nepal National Building Code, NBC 201: 1994
- Mandatory Rules of Thumb Reinforced Concrete Buildings without Masonry Infill, Nepal National Building Code, NBC 205: 1994
- Timber, Nepal National Building Code, NBC 112: 1994
- Cold Formed Light Gauge Structural Steel Section, IS 811 (1987), or equivalent
- Design of Structural Timber in Building-Code of Practice , IS 883 (1994), or equivalent
- Code of Practice for Use of Cold Formed Light Gauge Steel Structural Members in General Building Construction, IS 801 (1975), or equivalent
- Reinforced Concrete: Building Code Requirements for Structural Concrete and Commentary, ACI 318M-08, American Concrete Institute
- Building Code Requirements and Specification for Masonry Structures, TMS 402-13/ACI 530-13/ASCE 5-13, American Concrete Institute
- Special Design Provisions for Wind and Seismic - 2015, ANSI / AWC SDPWS-2015, American Wood Council
- Mandatory Rules of Thumb Reinforced Concrete Buildings without Masonry Infill, Nepal National Building Code, NBC 205: 1994

- Structural Steel: Specification for Structural Steel Buildings, ANSI/AISC 360-10, American Institute of Steel Construction
- Seismic Provisions for Structural Steel Buildings, ANSI/AISC 341-10, American Institute of Steel Construction
- North American Specification for the Design of Cold-formed Steel Structural Members, AISI Standard

Other References

- Seismic Evaluation and Retrofit of Existing Buildings, ASCE/SEI 41-13, American Society of Civil Engineers
- Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-10, American Society of Civil Engineers
- Assessment of First Generation Performance-based Seismic Design Methods for New Steel Buildings, Volume 1: Special Moment Frames, NIST Technical Note 1863-1, National Institute of Standards and Technology
- NEHRP Seismic Design Technical Brief No. 1, Seismic Design of Reinforced Concrete Special Moment Frames, NIST GCR 8-917-1, National Institute of Standards and Technology
- NEHRP Seismic Design Technical Brief No. 2, Seismic Design of Steel Special Moment Frames, NIST GCR 09-917-3, National Institute of Standards and Technology
- NEHRP Seismic Design Technical Brief No. 9, Seismic Design of Special Reinforced Masonry Shear Walls, NIST GCR 14-917-31, National Institute of Standards and Technology
- Seismic Hazard Mapping and Risk Assessment for Nepal 1994, NBC 400-V2. RV8, 18 November 1994
- Related research papers and reports

Chapter 2 Design Philosophy and Approach

2.1 Introduction

This chapter presents the design philosophy and approaches to be used in structural design of new school buildings.

2.2 Definitions

This section describes the definitions of the terms used in each building.

Remain elastic: Response of structural component up to first yield. When the force is applied to the component it stores strain energy, and when the force is removed this energy is recovered.

Gravity loads: Weight of structural components, partition, floor finishing, service equipment and live load.

Inelastic behavior: Response of structural component, in which some of the work done on the component as it deforms is dissipated, as plastic work, friction, facture energy, etc. An inelastic behavior will always be nonlinear.

DBE: Design Basis Earthquake. This earthquake is generally used in design, based on code procedures.

MCE: Maximum Considered Earthquake

Capacity design: A design process in which it is decided which components within a structural system will be permitted to yield (ductile components) and which components will remain elastic (brittle components). The components are designed in such a way that plastic hinges can form only in predetermined positions and in predetermined sequences. The concept of this method is to avoid brittle mode of failure.

Response spectrum: Spectrum presents the maximum acceleration response of the building due to ground shaking with respect to natural periods.

2.3 Overall Design Procedure

Two methods are mentioned that the structural designer would select in consultation with DoE/DUDBC.

2.3.1 Design Procedure 1

Analysis and design of the school buildings shall be performed according to the following steps for each structural system.

1) Develop the structural system/concept for each structural system. Use the basic structural systems described in Table 1.1 as a guideline.
2) Create the finite element model with varying complexity and refinement suitable for developing understanding the response. Carry out different types of analysis to determine the response of the building under gravity and lateral loadings.
3) Design the structural components to remain elastic under gravity and wind loads and provide well-defined inelastic behavior where nonlinear response occurs under DBE level earthquake, as appropriate. Capacity design approach will be used for the response of members to remain elastic under DBE level earthquake, as appropriate. Linear, response spectrum analysis should be conducted for DBE level earthquake with response reduction

factor to determine the response of the building. Design is carried out in accordance with the relevant provisions of the latest national building code provisions.

4) As design would be typical schools which will be replicated for several sites, the performance of the building should be evaluated after substantial completion of design in accordance with code procedures mentioned in step 3. Performance of the building shall be evaluated with an objective to provide Life Safety performance level under 1000-year return period earthquakes. Optionally, Collapse Prevention performance level under 2000-year return period earthquake may be checked. Pushover analysis shall be conducted as minimum requirements. Overall response, such as transient drifts, residual drifts, and deformation and strength capacity requirements of components are checked.

5) If the performance based on global building and local component responses does not meet the acceptance criteria, carry out step 1 to 4 to enhance the structural performance of the building.

6) If the performance based on global building and local component responses meet the acceptance criteria, structural design drawings shall be prepared for construction.

Regarding "Design Procedure 1", to refer to the Chapter 3, 4, 5, 6, and 7.1 to 7.4.2 is required.

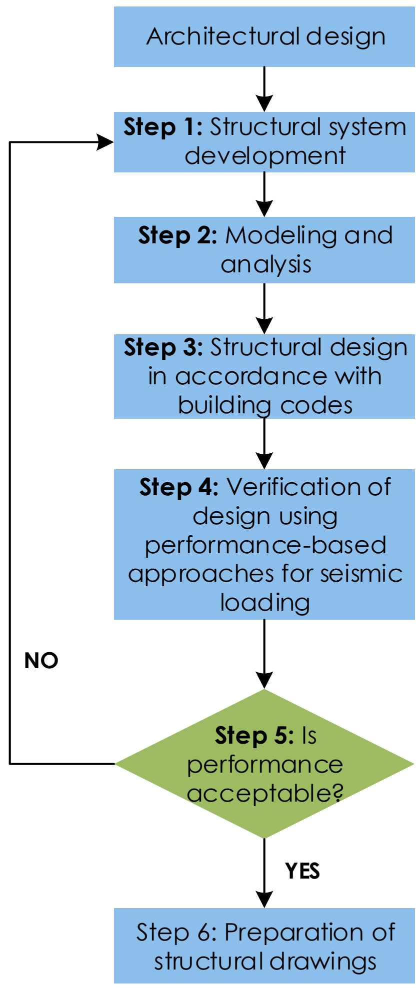

Figure 2-1 : Overall Design Procedure 1

2.3.2 Design Procedure 2

Analysis and design of the school buildings shall be performed according to the following steps for each structural system.

1) Develop the structural system/concept for each structural system. Use the basic structural systems described in Table 1.1 as a guideline.
2) Create the finite element model with varying complexity and refinement suitable for developing understanding the response. Carry out different types of analysis to determine the response of the building under gravity and lateral loadings.
3) Design the structural components under gravity, seismic loads and wind loads. Design shall be carried out in accordance with both Nepal National Building Code (NBC) and latest Indian Standards (IS), and shall satisfy both codes.
4) After designing in accordance with NBC and IS, it is preferable to evaluate the performance of the building by pushover analysis. Pushover analysis will be conducted to determine the displacement ductility factor “μ”. Response reduction factor, R will be calculated based on ductility factor “μ”. Here R factor based on IS (code-based design) can be defined as “R_c” and also based on performance-based can be defined as “R_p”.
5) If the result of R and K are

   $R_c > R_p$, calculate code-based design again by using R_p .

   In case, $R_c \leq R_p$, it is not necessary to redo the code-based design.
6) Structural design drawings shall be prepared for construction.

Regarding “Design Procedure 2”, it’s necessary to refer to the Chapter 7.4.3. In addition, the sentence relating to the original NBC and IS in Chapter 3, 4, 5, and 6 needs to be taken into account.

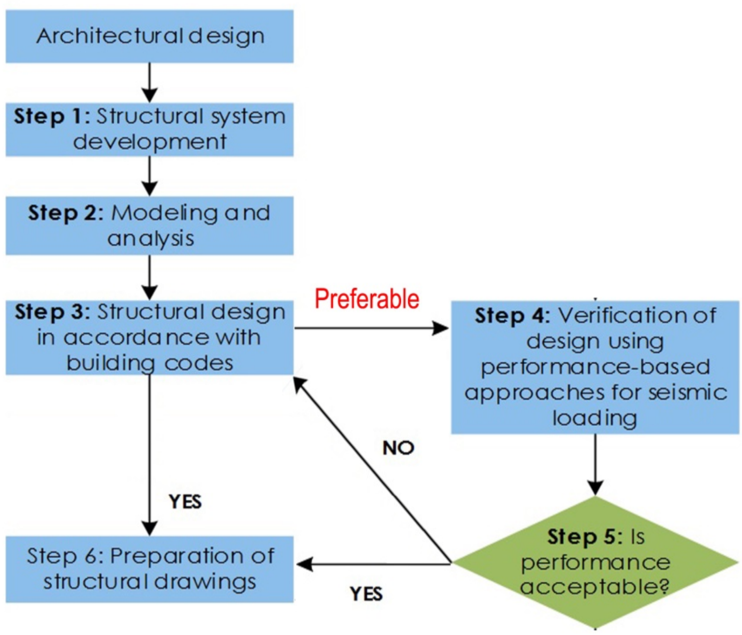

Figure 2-2 : Overall Design Procedure 2

Chapter 3 Basic Materials

3.1 Introduction

This chapter presents the strength of materials used in the design of structural components.

3.2 Concrete

The minimum compressive strength measured at 28 days, for the cylinder specimen used in different types of structural components are shown in the following table. Higher values may be used based on the discretion of the engineer.

Table 3-1 : Compressive Strength of concrete

Standard	Member	f'_c (Nominal) (MPa)	f'_c (Expected) (MPa)
NBC 205:1994	Footings	16	20.8
NBC 205:1994	Beams	16	20.8
NBC 205:1994	Columns	16	20.8

3.3 Reinforcing Steel

Minimum yield strength of reinforcing steel to be used in the design is shown in the following table.

Table 3-2 : Yield Strength of Reinforcing steel

Standard	Diameter	f_y (Nominal) (MPa)	f_y (Expected) (MPa)
NBC 205:1994	12 mm and above	415	518
NBC 205:1994	10 mm and below	250	313

3.4 Structural Steel

Yield strength of structural steel used in the design is shown in the following table.

Table 3-3 : Yield Strength of Structural Steel

Standard	Section	F_y (Nominal) (MPa)	F_u (Nominal) (MPa)	F_y (Expected) (MPa)	F_u (Expected) (MPa)
IS 800:1984	Wide flange shapes	250	410	275	451
IS 800:1984	Angle and channel sections	250	410	275	451
IS 800:1984	Miscellaneous plates and connection materials	250	410	275	451

3.5 Cold-formed Steel

Minimum yield strength of cold-formed steel used in the design is shown in the following table.

Table 3-4 : Yield Strength of Cold-formed Steel

Standard	Section	F_y (Nominal) (MPa)	F_u (Nominal) (MPa)	F_y (Expected) (MPa)	F_u (Expected) (MPa)
IS:801-1975	Channel	250	410	275	451

3.6 Masonry

Minimum strength of masonry used in the design is shown in the following table.

Table 3-5 : Strength of Masonry Prism

Element	Strength	Nominal (MPa)	Expected (MPa)
Burnt clay bricks	Compressive strength	2.07	2.7
Compressed soil cement blocks	Compressive strength	2.71	2.71

3.7 Timber

Material properties shall be in accordance with NBC 112:1994 or IS 883-1994 .

Chapter 4 Loads

4.1 Introduction

This chapter presents the design loads considered in the structural design, including gravity loads, seismic loads and wind loads.

4.2 Gravity Load

Self-weight of the structure is considered as dead load and finishes and partitions are considered as superimposed dead load. Live load is determined in accordance with occupancy or use. The following loads are in addition to the self-weight of the structure. The minimum loading requirements shall be taken from IS 875 (Part 2)-1987 or equivalent.

Table 4-1 : Live Load and Superimposed Dead Load

Occupancy or Use	Live Load	Superimposed Dead Load
Classrooms	3.0 kPa	To be computed for actual finishes and partitions
Corridors	4.0 kPa	To be computed for actual finishes and partitions
Roof	0.75 kPa	

4.3 Wind Load

Wind speed shall be determined in accordance with NBC 104-1994. The country is divided into two regions: a) the lower plains and hills and, b) the mountains. The first zone generally includes the southern plains of the Terai, the Kathmandu Valley and those regions of the country generally below an elevation of 3000 meters. The second zone covers all areas above 3000 meters. For the Nepalese plains continuous with the Indian planes, a basic velocity of 47 m/s shall be used. In the higher hills, a basic wind velocity of 55 meters per second shall be used.

Table 4-2 : Parameters for Wind Loading

Parameter	Value
Basic wind speed	To be determined based on building location
Terrain category	To be determined based on building location

4.4 Seismic Load

For design procedure 1, the basic seismic input shall be determined from NBC. 500-year return period earthquake shall be used as Design Basis Earthquake in code-based design. The performance shall be checked for Life Safety performance level under 1000-year return period earthquake, and optionally Collapse Prevention performance level under 2000-year return period earthquake.

For design procedure 2, the seismic input used in code-based design shall be Design Basis Earthquake mentioned in latest NBC and IS.

Table 4-3 : Parameters for Seismic Loading

Parameter	Value
Zone factor, Z (NBC 105-1994) Zone factor, Z (IS 1893-2002)	1 0.36
Importance factor	1.5
Soil type	II (Needs to be determined based on building location)
Structural performance factor, K	• System 1 = 2 • System 2 = 1 • System 3 = 4 • System 4 = 1 • System 5 = 4 • System 6 = 4 • System 7 = 4
Response reduction factor, R	• System 1 = 1.5** • System 2 = 5 • System 3 = 3 • System 4 = 5 • System 5 = 3** • System 6 = 3** • System 7 = 1.5**
C_a*	• 500-yr = 0.36 • 1000-yr = 0.46 • 2000-yr = 0.58
C_v*	• 500-yr = 0.45 • 1000-yr = 0.58 • 2000-yr = 0.73

* Used in design procedure 1.

** Assumed R value since the values are not available in IS1893-2002.

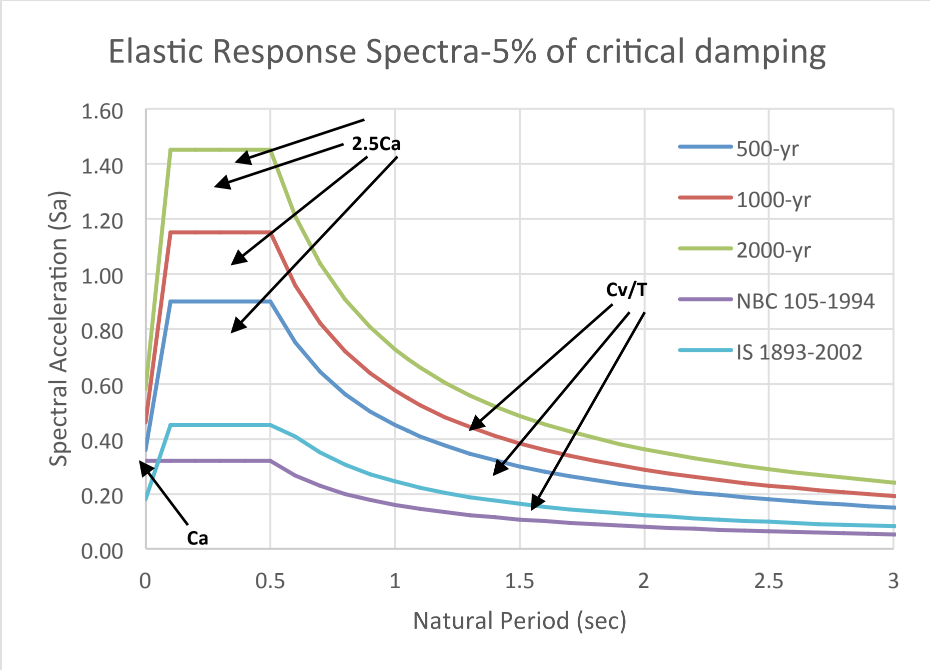

Figure 4-1 : Response Spectra for Earthquakes with Different Return Periods for Soil Type II (Medium Soil Sites) (Ref: Figure 7.1b, Hazard Spectra for Kathmandu (Kawashima Attenuation Model, GC 2, 5% Damping, NBC 400 V2.RV8-1994)

Note: Importance factor of 1 is used in the figure for comparison.

Response spectrum curve for NBC 105-1994 is based on K=4.

4.5 Load Combinations

4.5.1 Code-based Design

4.5.1.1 Ultimate Strength Design

Ultimate strength design load combinations used in code-based design are shown in the following table. (Ref: NBC 105:1994, NBC 110:1994, IS 875-1987)

Table 4-4 : Ultimate Strength Design Load Combinations used in Code-based Design

No.	Load Combination
1	1.4D + 1.5L
2	1.0D + 1.25W
3	1.0D + 1.3L + 1.25W
4	1.0D + 1.25W
5	1.0D + 1.3L + 1.25E
6	0.9D + 1.25E

Where: D = Dead load

L = Live load

E = Effects of forces at DBE level

W = Wind load

Live load is not included in the mass calculations.

Vertical seismic load effect shall be considered, taken as two-thirds of design horizontal response spectrum.

4.5.1.2 Allowable Stress Design

Allowable stress design load combinations used in code-based design are shown in the following table. (Ref: NBC 105:1994, NBC 110:1994, IS 875-1987)

Table 4-5 : Allowable Stress Design Load Combinations used in Code-based Design

No.	Load Combination
1	D
2	D + L
3	D + L + W
4	0.7D + W
5	D + L + E
6	0.7D + E

4.5.2 Performance Evaluation

Load combinations used in performance evaluation are shown in the following table.

No.	Load Combination
1	1.0D + 0.25 L ± 1.0 E

Where: D = Dead load

L = Live load

E = Earthquake load

Live load is not included in the mass calculations.

Chapter 5 Structural Systems

5.1 Introduction

This chapter presents the basic structural systems to be used in design of school buildings.

5.2 Different Structural Systems

5.2.1 Ordinary Reinforced Concrete Moment Resisting Frames and Masonry Infill Walls

Masonry infill walls shall be considered as primary seismic force resisting system and moment frame will be act as backup system for ductility. The frames and infill walls shall resist the total lateral force in accordance with their relative rigidities, considering the interaction of the infill walls and frames. Referring to Table 16-N, UBC-97, overstrength factor, R for ordinary reinforced concrete moment resisting frame is 3.5, in which effect of masonry infill walls are not considered. In NBC-105, structural performance factor, K for ductile moment resisting frame is 1 and frame with masonry infills is 2. Response reduction factor is 2 times difference between moment frame with masonry infills and moment frame without masonry infills. Hence, overstrength factor, R of 1.5 would be used for ordinary reinforced concrete moment resisting frame with masonry infills for seismic loading in accordance with UBC-97.

Unreinforced masonry infill walls shall be designed as shear infill panels to act as seismic force resisting system. Shear infill panels shall be in full contact with the frame elements on all four sides. Refer to TMS 402-13/ACI 530-13/ASCE 5-13, Appendix B, the infill wall shall be designed as participating infills. The infills shall be supported out-of-plane by connectors attached to the bounding frame. Infills shall be designed for in-plane shear forces and out-of-plane flexural demand.

Each bounding column shall be designed to resist the shear and moment demand equal not to less than 1.1 multiplied by the results from the equivalent strut frame analysis, and for axial force not less than the results from that analysis. In addition, the design shear at each end of the column shall be increased by the horizontal component of the equivalent strut force acting on that end under design loads. Each bound beam shall be designed to resist the shear and moment equal to at least 1.1 multiplied by the results from the equivalent strut frame analysis and for an axial force not less than the results from that analysis. In additional the design shear at each end of the beam shall be increased by the vertical component of the equivalent strut force acting on that end under design loads.

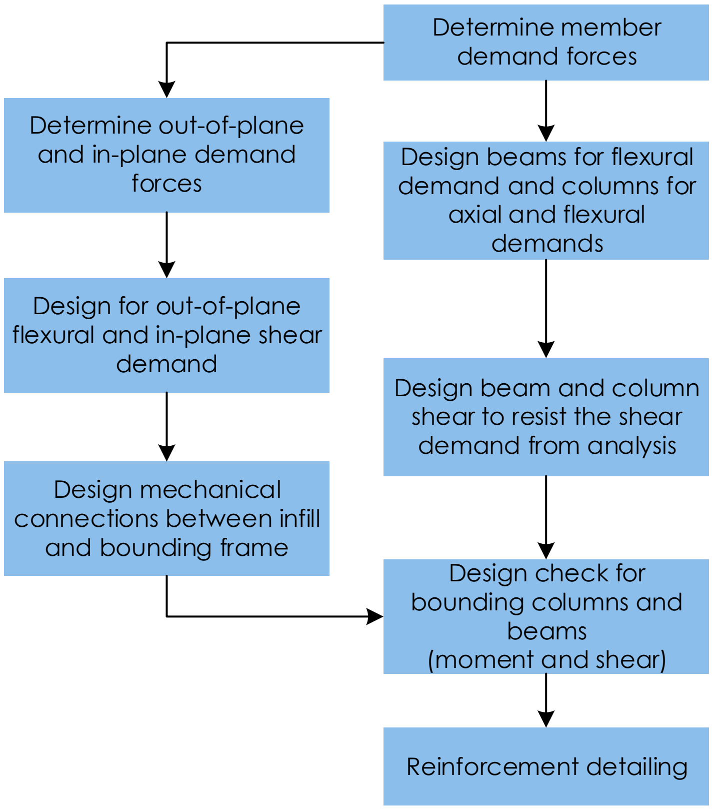

Figure 5-1 : Design Procedure for Ordinary Reinforced Concrete Moment Resisting Frames with Masonry Infill Walls

5.2.2 Special Steel Moment Resisting Frames

Beams, columns, and beam-column connections in special steel moment frames are proportioned and detailed to resist flexural, axial, and shearing actions that result as a building sways through multiple inelastic displacement cycles during strong earthquake ground shaking. Special proportioning and detailing requirements are therefore essential in resisting strong earthquake shaking with substantial inelastic behavior. Three main objectives of special steel moment resisting frame are:

1) To achieve a strong-column/weak-beam condition that distributes inelastic response over several stories
2) To avoid P-delta instability under gravity loads and anticipated lateral seismic drifts
3) To incorporate details that enable ductile flexural response in yielding regions.

It is important to avoid early formation of inelastic response which is dominated by formation of plastic hinges at the tops and bottoms of columns within a single story. When such story mechanisms form, it would result very large P-delta effects at those locations. In order to avoid this, formation of side sway mechanisms dominated by hinging of beams is preferable, as opposed to column hinging.

In a severe earthquake, frame structures have the potential to collapse in a side sway mode due to P-delta effects. These effects are caused by vertical gravity loads acting on the deformed configuration of the structure. Second order analysis shall be conducted to consider P-delta effects.

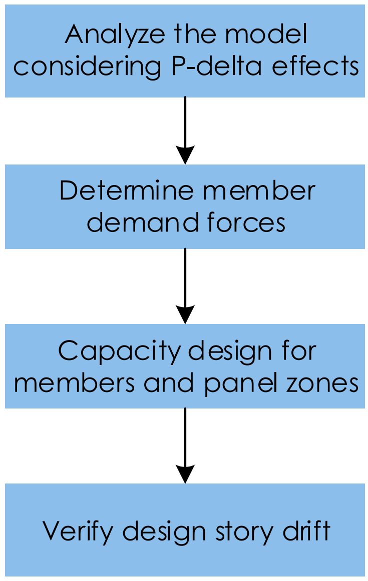

Figure 5-2 : Design Procedure for Special Steel Moment Resisting Frames

5.2.3 Reinforced Interlocking Bearing Walls

Reinforced interlocking bearing wall system shall be designed to resist the lateral loading and gravity loads. A reinforced interlocking bearing wall system is composed of wall segments, each of which can be categorized as either flexure-dominated or shear-dominated. A flexure-dominated wall segment is one whose inelastic response is dominated by deformations resulting from the tensile yielding of flexural reinforcement. A shear-dominated segment is one whose inelastic response is dominated by diagonal shear (tension) cracks. It can be checked whether a wall segment is flexure-dominated or shear-dominated by comparing its flexural capacity with its shear capacity. A flexure-dominated segment has a lower flexural capacity than shear capacity; for a shear-dominated segment, the opposite is true.

The ductility capacity of flexure-dominated walls depends on the aspect ratio, the flexural reinforcement percentage, and the axial load. Flexure-dominated elements are generally ductile. Shear-dominated elements are generally brittle, with failure characterized by diagonal shear cracks.

When a reinforced interlocking wall has a shear-span-to-depth ratio $M_u/(V_u d_v)$ greater than one with a well-designed plastic hinge zone, these requirements plus the required capacity-based design for shear generally result in flexure-dominated, ductile behavior. However, when a reinforced interlocking wall has a shear-span-to-depth ratio less than one or a high axial load, the same combination of prescriptive requirements may still result in a wall that is shear-dominated and brittle.

To protect a reinforced interlocking wall against shear failure caused by possible flexural over strength, the design shear strength, ΦV_n , should exceed the shear corresponding to the development of the nominal moment capacity by a factor of at least 1.25.

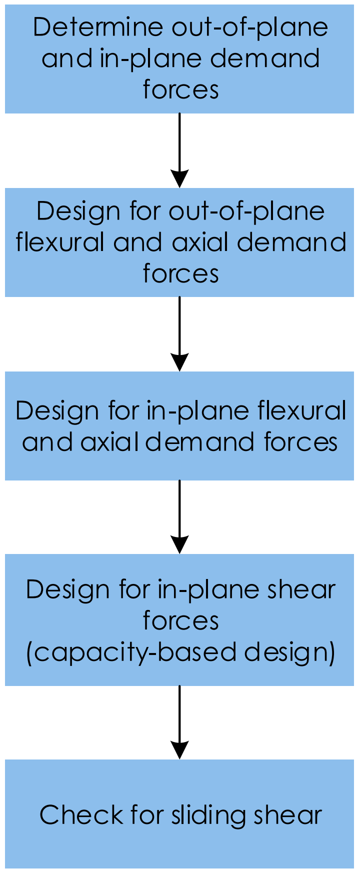

Figure 5-3 : Design Procedure for Reinforced Interlocking Bearing Walls

5.2.4 Special Reinforced Concrete Moment Resisting Frame

Special reinforced concrete moment resisting frames shall be proportioned and detailed in such a way that the frame undergo safely extensive inelastic deformations that are anticipated under earthquakes.

Three main objectives of special reinforced concrete moment resisting frame are:

1) To achieve a strong-column/weak-beam design that spreads inelastic response over several stories
2) To avoid shear failure
3) To provide details that enable ductile flexural response in yielding regions.

When the building sways during an earthquake, the distribution of damage over height depends on the distribution of lateral drift. If the building has weak columns, drift tends to concentrate in one or a few stories, and may exceed the drift capacity of columns. Additionally, the columns in a given story support the weight of the entire building above those columns, whereas the beams only support the gravity loads of the floor of which they form a part; therefore, failure of a column is of greater consequence than failure of a beam.

Ductile response requires that members yield in flexure, and that shear failure be avoided. Shear failure, especially in columns, is relatively brittle and can lead to rapid loss of lateral strength and axial load-carrying capacity. Flexural yielding regions shall be designed for code-required moment strengths, and then calculate design shears based on equilibrium assuming the flexural yielding regions develop probable moment strengths. Hoops typically are provided at the ends of columns, as well as through beam-column joints, and at the ends of beams in order to improve the ductile behavior.

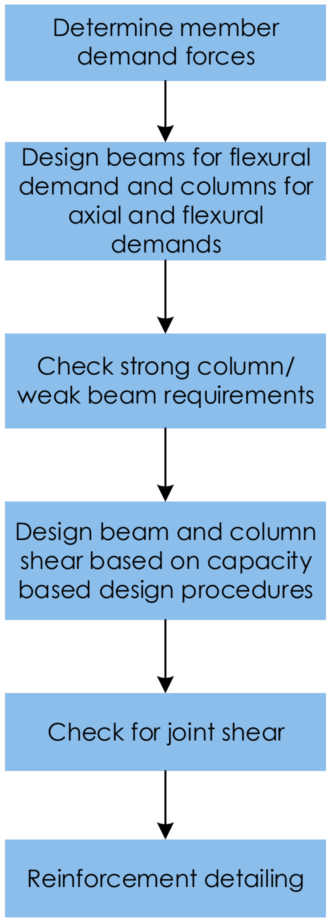

Figure 5-4 : Design Procedure for Reinforced Concrete Special Moment Resisting Frame

5.2.5 Cold-Formed Steel Ordinary Moment Frame

Cold-formed steel ordinary moment resisting frames shall be proportioned and detailed in such a way that the frame will remain essentially elastic or design the higher strength to reduce the high ductility demands under earthquakes. As the mass of structural system is small, the design will be primarily governed by wind loading.

5.2.6 Hot-Rolled Steel Ordinary Moment Frame

Hot-rolled steel ordinary moment resisting frames shall be designed and detailed for higher strength to reduce the high ductility demands.

5.2.7 Timber Structure

Wood-frame shear walls sheathed with shear panels of particle board, structural fiber board, and gypsum wall board are used to resist the seismic forces. Bearing wall system category would be applicable because shear walls used for seismic force resistance also function to support gravity loads of a building.

Chapter 6 Code-based Design

6.1 Introduction

This chapter presents the finite element modeling, analysis and design procedures to be used in the code-based design of school buildings.

6.2 Modeling of Structural System

A complete, three-dimensional elastic models are created, representing the structure's spatial distribution of the mass and stiffness to an extent that is adequate for the calculation of the significant features of the building's elastic response. SAP2000 is used as analysis tool. The elastic models are used for gravity, wind and DBE level earthquake analysis. Nominal material properties are used in modeling of structural components. The models include footings, columns, beams, walls, and roof truss. Recommended element types and stiffness modifiers to be used in the modeling of different types of components are summarized in the following table.

Table 6-1 : Modeling of Structural System for Code-based Design

Structural System	Component	Element to be Used	Wind	DBE
System 1	RC beams	Frame	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 0.35 I_g Shear – 1.0 A_g
	RC columns	Frame	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 0.7 I_g Shear – 1.0 A_g
	Masonry infill walls	Shell or frame (to model strut)	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g	In-plane Flexural – 0.15 I_g Shear – 0.35 A_g Out-of-plane Flexural – 0.1 I_g Shear – 0.2 A_g
	Footing	Shell	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g
	Roof truss	Frame	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g
System 2	Steel beams	Frame	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 1.0 I_g Shear – 1.0 A_g
	Steel columns	Frame	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 1.0 I_g Shear – 1.0 A_g
	Footing	Shell	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g
	Roof truss	Frame	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g
System 3	Reinforced interlocking	Layered shell	In-plane Flexural – 1.0 I_g	In-plane Flexural – 0.15 I_g

Structural System	Component	Element to be Used	Wind	DBE
	bearing walls		Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g	Shear – 0.35 A_g Out-of-plane Flexural – 0.1 I_g Shear – 0.2 A_g
	Footing	Shell	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g
	Roof truss	Frame	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g
System 4	RC beams	Frame	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 0.35 I_g Shear – 1.0 A_g
	RC columns	Frame	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 0.7 I_g Shear – 1.0 A_g
	Footing	Shell	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g
	Roof truss	Frame	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g
System 5	Cold-formed steel beams	Frame	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 1.0 I_g Shear – 1.0 A_g
	Cold-formed steel columns	Frame	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 1.0 I_g Shear – 1.0 A_g
	Footing	Shell	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g
	Roof truss	Frame	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g
System 6	Hot-rolled steel beams	Frame	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 1.0 I_g Shear – 1.0 A_g
	Hot-rolled steel columns	Frame	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 1.0 I_g Shear – 1.0 A_g
	Footing	Shell	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g
	Roof truss	Frame	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g
System 7	Timber beams	Frame	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 1.0 I_g Shear – 1.0 A_g

Structural System	Component	Element to be Used	Wind	DBE
	Timber columns	Frame	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 1.0 I_g Shear – 1.0 A_g
	Shear panels	Shell	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g
	Footing	Shell	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g
	Roof truss	Frame	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g

6.2.1 Beams

Frame elements are used in modeling of beams, which includes the effects of bending, torsion, axial deformation, and shear deformations. Insertion points and end offsets are applied to account for the finite size of beam and column intersections, if required. The end offsets may be made partially or fully rigid based on engineering judgment to model the stiffening effect that can occur when the ends of an element are embedded in beam and column intersections. End releases are applied to model different fixity conditions at the ends of the element in accordance with the type of detailing.

6.2.2 Roof Truss

Frame elements are used in modeling of truss. End releases are applied to model different fixity conditions at the ends of the element in accordance with the type of detailing.

6.2.3 Columns

Frame elements are used in modeling of columns, which includes the effects of biaxial bending, torsion, axial deformation, and biaxial shear deformations. Insertion points and end offsets are applied to account for the finite size of beam and column intersections, if required. The end offsets may be made partially or fully rigid based on engineering judgment to model the stiffening effect that can occur when the ends of an element are embedded in beam and column intersections. End releases are applied to model different fixity conditions at the ends of the element in accordance with the type of detailing.

6.2.4 Footings

Shell elements are used in modeling of footings. The effect of soil structure interaction is considered for the buildings in which an increase in fundamental period due to soil effects will result in an increase in spectral accelerations. Vertical springs and lateral springs are assigned respectively in order to consider the interaction effect of soil. The spring stiffness values are calculated based on the sub-grade modulus values from geotechnical report if available. Approximate sub-grade modulus values can be estimated based on the empirical formulas mentioned below.

$K = 3\ E_s$ for cohesionless soil

$K = 1.6\ E_s$ for cohesive soil

Vertical spring stiffness may be determined based on the allowable bearing capacity as below. Horizontal spring stiffness may be assumed 50% of vertical spring stiffness.

K_v = Allowable bearing capacity x Safety factor x 40

6.2.5 Masonry Infill Walls

Masonry infill walls can be modeled in two options as below.

1) *Using Shell Element*

Shell elements shall be used in modeling of unreinforced masonry infill walls, which include the membrane and plate bending behavior. The wall elements are meshed horizontally and vertically in adequate numbers. The orientation of local axis of the shear wall elements shall be consistent in entire wall. Unreinforced masonry walls may be checked to resist out-of-plane inertial forces as isolated components spanning between floor levels, and/or spanning horizontally between columns and pilasters.

2) *Using Strut Element*

Equivalent strut model, capable of resisting compression only, can be used. The section size of equivalent strut shall be determined in accordance with TMS 402-13/ACI 530-13/ASCE 5-13, Section B.3.4.1. Strut element shall be released at each end for moments about 2 and 3 axes. Tension limit shall be set to zero for the strut elements. Nonlinear analysis shall be conducted to consider the compression only strut.

6.2.6 Reinforced Interlocking Bearing Walls

Layered shell elements are used in modeling of reinforced interlocking bearing walls. The entire cross section of the wall is discretized into individual layers. These layers are located by a specific distance from the reference surface and with the specified thickness. The material properties of each layer are specified by the properties of each material. The elements are meshed horizontally and vertically in adequate numbers. The orientation of local axis of the shear wall elements shall be consistent in entire wall. In layered element, mass and weight are computed for membrane and shell layers, not for plate layers.

6.2.7 Damping

5% constant modal damping is used in seismic analysis at DBE level.

6.3 Analysis Procedures

Analysis procedures to be used for code-based design are presented in the following sections.

Table 6-2 : Analysis Procedures used in Code-based Design

Load Case	Analysis
Gravity and wind	Linear static analysis
Earthquake	Response spectrum analysis

6.3.1 Modal Analysis

Modal analysis is carried out to determine the modal properties of the building. 100% of dead load, superimposed dead load and 25% of live load are considered as mass source in modal analysis. Either Eigen analysis or Ritz analysis shall be used. Sufficient number of vibration modes shall be considered to achieve at least 90% of participating mass of the building.

6.3.2 Linear Static Procedure (LSP)

Linear static analysis is carried out for gravity and wind loadings. Wind load may be applied to the exposure from walls and roofs in the analysis model.

6.3.3 Response Spectrum Analysis (RS)

Response spectrum analysis is carried out using linearly elastic response spectra. At least 90% of the participating mass of the building is considered in each of two orthogonal principal directions of the building. Complete Quadratic Combination (CQC) rule is used for combination of responses from each mode. Orthogonal effects are considered by designing elements for 100 percent of the prescribed design seismic forces in one direction plus 30 percent of the prescribed design seismic forces in the perpendicular direction. 5% constant modal damping is considered in the analysis.

6.4 Component and Member Design

The structural components are designed to satisfy the strength and ductility requirements. Strength capacity for different types of actions considered in the design are summarized in the table below.

Table 6-3 : Component and Member Design

Structural System	Component	Design Approach/Consideration	Code Reference
System 1	RC beams	Flexural, Shear	ACI 318-08 Chapter 10, 11 and 21
	RC columns	PMM, Shear	ACI 318-08 Chapter 10, 11 and 21
	Masonry infill walls	Out-of-plane flexural and in-plane shear	ACI 530-13, Appendix B
	Footings	Bearing capacity of soil Flexural, shear	ACI 318-08 Chapter 15
	Steel truss		AISC 360-10 Chapter D and E
	Steel connections		AISC 360-10 Chapter J
System 2	Steel beams	Flexural response • Flexural yielding • Lateral-torsional buckling • Flange local buckling • Web local buckling	AISC 360-10 Chapter F and G

Structural System	Component	Design Approach/Consideration	Code Reference
		Shear	
	Steel columns	Compression • Flexural buckling • Torsional and flexural-torsional buckling Flexure • Flexural yielding • Lateral-torsional buckling • Flange local buckling • Web local buckling Shear	AISC 360-10 Chapter E and H
	Footings	Bearing capacity of soil Flexural, shear	ACI 318-08 Chapter 15
	Steel truss	Compression • Flexural buckling • Torsional and flexural-torsional buckling Tension	AISC 360-10 Chapter D and E
	Steel connections	Moment connections Shear connections	AISC 360-10 Chapter J
System 3	Reinforced interlocking bearing walls	Bearing, axial compression In-plane flexural and shear Out-of-plane flexural	ACI 530-13 as appropriate and test results
	Footings	Bearing capacity of soil Flexural, shear	ACI 318-08 Chapter 15
	Steel truss	Compression • Flexural buckling • Torsional and flexural-torsional buckling Tension	AISC 360-10 Chapter D and E
	Steel connections	Moment connections Shear connections	AISC 360-10 Chapter J
System 4	RC beams	Flexural, Shear	ACI 318-08 Chapter 10, 11 and 21
	RC columns	PMM, Shear	ACI 318-08 Chapter 10, 11 and 21
	Footings	Bearing capacity of soil Flexural, shear	ACI 318-08 Chapter 15
	Steel truss	Compression	AISC 360-10

Structural System	Component	Design Approach/Consideration	Code Reference
		• Flexural buckling • Torsional and flexural-torsional buckling Tension	Chapter D and E
	Steel connections	Moment connections Shear connections	AISC 360-10 Chapter J
System 5	Cold-formed steel beams	Flexural response Shear	AISI-Commentary Chapter C
	Cold-formed steel columns	Compression Flexure Shear	AISI-Commentary Chapter C
	Footings	Bearing capacity of soil Flexural, shear	ACI 318-08 Chapter 15
	Steel truss	Compression Tension	AISI-Commentary Chapter C
	Steel connections	Moment connections Shear connections	AISC 360-10 Chapter J
System 6	Steel beams	Flexural response • Flexural yielding • Lateral-torsional buckling • Flange local buckling • Web local buckling Shear	AISC 360-10 Chapter F and G
	Steel columns	Compression • Flexural buckling • Torsional and flexural-torsional buckling Flexure • Flexural yielding • Lateral-torsional buckling • Flange local buckling • Web local buckling Shear	AISC 360-10 Chapter E and H
	Footings	Bearing capacity of soil Flexural, shear	ACI 318-08 Chapter 15
	Steel truss	Compression • Flexural buckling • Torsional and flexural-torsional buckling	AISC 360-10 Chapter D and E

Structural System	Component	Design Approach/Consideration	Code Reference
		Tension	
	Steel connections	Moment connections Shear connections	AISC 360-10 Chapter J
System 7	Timber beams	Flexural, Shear	ANSI / AWC SDPWS-2015, NBC 112:1994, IS-883:1994
	Timber columns	PMM, Shear	ANSI / AWC SDPWS-2015, NBC 112:1994, IS-883:1994
	Shear panels	Out-of-plane flexural and in-plane shear	ANSI / AWC SDPWS-2015, NBC 112:1994, IS-883:1994
	Footings	Bearing capacity of soil Flexural, shear	ACI 318-08 Chapter 15
	Timber truss		ANSI / AWC SDPWS-2015, NBC 112:1994, IS-883:1994
	Connections		ANSI / AWC SDPWS-2015, NBC 112:1994, IS-883:1994

Chapter 7 Seismic Performance-based Evaluation

7.1 Introduction

This chapter presents the modeling, analysis and evaluation procedures used in seismic performance-based evaluation of school buildings. For design procedure 1, structural performance of the building shall be evaluated under 1000-year return period and 2000-year return period (optional) earthquakes. For design procedure 2, response reduction factor, R factor will be determined based on the function of ductility factor, μ, regardless of seismic demand level.

7.2 Modeling of Structural System

For seismic performance-based evaluation, nonlinear verification models are used, in which deformation-controlled actions are modeled as nonlinear while force-controlled actions are modeled as linear.

The model includes inelastic properties for components that are anticipated to be loaded beyond their elastic limits. These include flexural response of beams, columns, in-plane response of unreinforced masonry infills and reinforced interlocking walls. Elements that are assumed to remain elastic are modeled with elastic member properties. These include shear response of beams and columns, flexural and shear response of footings.

In design procedure 2, it is important to note that all force-controlled actions shall be modeled with force-controlled hinges. Force-controlled hinges shall lose the load carrying capacity when maximum force is reached. In deformation-controlled hinges, post-yielding stiffness and strength loss shall be properly defined.

Table 7-1 : Modeling of Structural System for Performance-based Evaluation

Structural System	Component	Element to be Used	1000-year	2000-year
System 1	RC beams	Frame with flexural hinges	Flexural – 0.35 I_g Shear – 1.0 A_g	Flexural – 0.3 Ig Shear – 1.0 Ag
	RC columns	Frame with PMM hinges	Flexural – 0.7 I_g Shear – 1.0 A_g	Flexural – 0.3 Ig Shear – 1.0 Ag
	Masonry infill walls	Nonlinear layered shell	<u>In-plane</u> Flexural – 0.15 I_g Shear – 0.35 A_g <u>Out-of-plane</u> Flexural – 0.1 I_g Shear – 0.2 A_g	<u>In-plane</u> Flexural – 0.15 I_g Shear – 0.25 A_g <u>Out-of-plane</u> Flexural – 0.1 I_g Shear – 0.2 A_g
	Footing	Shell	<u>In-plane</u> Flexural – 1.0 I_g Shear – 1.0 A_g <u>Out-of-plane</u> Flexural – 1.0 I_g Shear – 1.0 A_g	<u>In-plane</u> Flexural – 1.0 I_g Shear – 1.0 A_g <u>Out-of-plane</u> Flexural – 1.0 I_g Shear – 1.0 A_g
	Roof truss	Frame	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g
System 2	Steel beams	Frame with flexural hinges	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 1.0 I_g Shear – 1.0 A_g
	Steel columns	Frame with PMM hinges	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 1.0 I_g Shear – 1.0 A_g
	Footing	Shell	<u>In-plane</u>	<u>In-plane</u>

Structural System	Component	Element to be Used	1000-year	2000-year
			Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g
	Roof truss	Frame	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g
System 3	Reinforced interlocking bearing walls	Nonlinear layered shell	In-plane Flexural – 0.15 I_g Shear – 0.35 A_g Out-of-plane Flexural – 0.1 I_g Shear – 0.2 A_g	In-plane Flexural – 0.15 I_g Shear – 0.25 A_g Out-of-plane Flexural – 0.1 I_g Shear – 0.2 A_g
	Footing	Shell	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g
	Roof truss	Frame	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g
System 4	RC beams	Frame with flexural hinges	Flexural – 0.35 I_g Shear – 1.0 A_g	Flexural – 0.3 Ig Shear – 1.0 Ag
	RC columns	Frame with PMM hinges	Flexural – 0.7 I_g Shear – 1.0 A_g	Flexural – 0.3 Ig Shear – 1.0 Ag
	Footing	Shell	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g
	Roof truss	Frame	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g
System 5	Cold-formed steel beams	Frame with flexural hinges	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 1.0 I_g Shear – 1.0 A_g
	Cold-formed steel columns	Frame with PMM hinges	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 1.0 I_g Shear – 1.0 A_g
	Footing	Shell	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g
	Roof truss	Frame	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g
System 6	Hot-rolled beams	Frame with flexural hinges	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 1.0 I_g Shear – 1.0 A_g
	Hot-rolled columns	Frame with PMM hinges	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 1.0 I_g Shear – 1.0 A_g

Structural System	Component	Element to be Used	1000-year	2000-year
	Footing	Shell	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g	In-plane Flexural – 1.0 I_g Shear – 1.0 A_g Out-of-plane Flexural – 1.0 I_g Shear – 1.0 A_g
	Roof truss	Frame	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g	Axial – 1.0 A_g Flexural – 1.0 I_g Shear – 1.0 A_g

7.2.1 Beams

Frame elements are used in modeling of beams, which includes the effects of bending, torsion, axial deformation, and shear deformations. Nonlinear flexural hinges are assigned at the ends of beams to represent the nonlinear flexural response while shear response is modeled as linear.

7.2.2 Columns

Frame elements are used in modeling of columns, which includes the effects of biaxial bending, torsion, axial deformation, and biaxial shear deformations. Fiber P-M2-M3 hinges are used to model the nonlinear behavior of coupled axial force and bi-axial bending. Fiber hinges are assigned both ends of the column. User-defined fiber hinges are used, by generating the fiber layout from Section Designer. In reinforced concrete columns, rebar fibers are lumped while generating the fiber layout to reduce the analysis time. Plastic hinge length of reinforced concrete columns is determined based on the following equation.

$$L_p = 0.08\,L + 0.022\,f_{ye}d_{bl} \geq 0.044\,f_{ye}d_{bl}\ (\text{MPa})$$

Where

L_p = plastic hinge length

H = section depth

L = critical distance from the critical section of plastic hinge to the point of contraflexure

f_{ye} = expected yield strength of longitudinal reinforcement

d_{bl} = diameter of longitudinal reinforcement

7.2.3 Masonry Infill Walls and Reinforced Interlocking Bearing Walls

Nonlinear layered shell elements are used in nonlinear modeling of masonry infill walls and reinforced interlocking bearing walls. The procedure is same as linear modeling of reinforced interlocking bearing walls, except for considering nonlinear material behavior for concrete and reinforcement in in-plane response.

7.2.4 Damping

Rayleigh damping model is used. The damping ratios are provided as follows.

Table 7-2 : Damping Ratios

Period ratio T/T1	Damping Ratio
0.2	3 %
0.9	2%

Where, T1 is first mode natural period.

7.3 Analysis Procedures

Analysis procedures to be used for seismic performance-based evaluation are presented in the following sections.

Table 7-3 : Analysis Procedures used in Performance-based Evaluation

Load Case	Analysis
Gravity	Nonlinear static analysis
Earthquake	Nonlinear time history analysis (for design procedure 1) Pushover analysis (Nonlinear static, for design procedure 2)

7.3.1 Nonlinear Static Procedure for Gravity Load (NSP)

Nonlinear static analysis will be conducted for gravity loading, prior to lateral load analysis, using "Full Load" control application. In nonlinear static procedure, monotonically increasing gravity loading is applied on the building. P-Δ effects shall be considered in the analysis.

7.3.2 Nonlinear Time History Analysis (NLTHA)

Nonlinear time history analysis is carried out using pairs of ground motion records, analyzing simultaneously along each principal direction of the building. If fewer than seven time history analyses are performed, the maximum response is used for evaluation. If seven or more time history analyses are performed the average value of response is used. Nonlinear time history analysis is continued from the state end of gravity load case. Rayleigh damping model with 2-3% of critical damping is used (Specify damping by period). P-Δ effects are considered in the analysis.

The selected ground motion records for time history analysis should have magnitude, fault distances, and source mechanisms that are consistent with those that control the design earthquake ground motions for each seismic demand level. For each set of ground motion, the square root of sum of the squares (SRSS) of the 5%-damped response spectra of the scaled ground motion component shall be constructed. The sets of ground motion records shall be scaled such that the average value of the SRSS spectra does not fall below 1.3 times the 5%-damped spectrum for the design earthquake for periods between 0.2 T and 1.5 T (where T is the fundamental period of the building).

The PEER Ground Motion Database (PGMD) web-based tool (PEER, 2011) may be used for linear scaling and selecting ground motions to match with the design response spectrum of particular seismic level to be checked. The linear scaling factor for each ground motion should not be greater than 8.

7.3.3 Pushover Analysis

Firstly, nonlinear static analysis shall be performed for gravity loads using "Full Load" control application. Nonlinear static analysis for lateral loading shall be continued from the state end of gravity load case, using modal deformation load pattern, with "Displacement Control" application. P-Δ effects shall be considered in both gravity and lateral load cases.

7.4 Performance Criteria

This section presents the performance criteria to be used in seismic performance-based evaluation of school buildings.

7.4.1 Expected and Lower-Bound Strength used in Performance Evaluation

Where evaluating the behavior of deformation-controlled actions, the expected strength, Q_{CE}, shall be used. Where evaluating the behavior of force-controlled actions, a lower-bound estimate of the component strength, Q_{CL}, shall be used.

Expected Strength

Expected material properties shall be used to calculate the design strengths in accordance with the code based procedures, except strength reduction factor, Φ shall be taken equal to unity. Expected material properties may be calculated by multiplying lower-bound values by appropriate factors.

Table 7-4 : Factors to Translate Lower-Bound Material Properties to Expected Strength Material Properties

Material Property	Factor
Concrete compressive strength	1.3
Reinforcing steel tensile and yield strength	1.25
Masonry compressive strength	1.3
Masonry flexural tensile strength	1.3
Masonry shear strength	1.3
Structural steel yield strength	1.1

Note: Factor of 1.3 is used for concrete compressive strength in lieu of factor of 1.5, mentioned in Table 10-1, ASCE 41-13.

Lower-bound Strength

Lower-bound material properties shall be used to calculate the design strengths in accordance with the code based procedures, except strength reduction factor, Φ shall be taken equal to unity. Nominal material properties are used as lower-bound strength.

7.4.2 Performance Criteria for Design Procedure 1

Structural performance shall be satisfied for "Life Safety" performance level under 1000-year return period earthquakes and "Collapse Prevention" performance level under 2000-year return period earthquakes.

7.4.2.1 Global Response Acceptance Criteria

In lieu of other limits, the acceptance criteria for global response of the building is as below.

Table 7-5 : Acceptance Criteria for Global Response of School Buildings

Type	Seismic Level	
	DBE	MCE
Story drift		
• System 1	0.5%	0.6%
• System 2	1.5%	3%
• System 3	0.6%	1.5%
• System 4	1.5%	3%
• System 5	1.5%	3%
Foundation		
• Total settlement	6 in.	Major settlement and tilting
• Differential settlement in 30 ft	0.5 in.	
• Sliding	FS ≥ 1.5	FS ≥ 1.5
• Overturning	FS ≥ 1.5	FS ≥ 1.5

7.4.2.2 Component Response Acceptance Criteria

Actions in all lateral load resisting elements are categorized as either force-controlled or deformation-controlled actions. Following table summarizes the classification of component actions.

Deformation-Controlled Actions

The response of the components under deformation-controlled actions shall be checked in accordance with the acceptance criteria for nonlinear procedures mentioned through Chapters 8 through 11 of ASCE 41-13.

Force-Controlled Actions

The response of the components under force-controlled actions shall be checked using the lower-bound strengths which shall not be less than maximum design forces or maximum design forces developed as limited by the nonlinear response of the component.

Table 7-6 : Classification of Actions and Acceptance Criteria

Structural System	Component	Deformation-Controlled		Force-Controlled	Reference
		Action	NL Response	Action	
System 1	RC beams	• Moment	• Hinge rotation	• Shear	ASCE 41-13, Table 10-7
	RC columns	• PMM	• Hinge rotation	• Axial compression • Shear	ASCE 41-13, Table 10-8
	Masonry infill walls[3]	• In-plane shear	• In-plane rotation (Drift)	• Column shear adjacent to infill panels • Beam shear adjacent to infill panels	ASCE 41-13, Table 11-9, 11-10
	Footing	-	-	Bearing capacity of soil Flexural, shear	ACI 318-08 Chapter 15
	Steel truss			Compression • Flexural buckling • Torsional and flexural-torsional buckling Tension	AISC 360-10 Chapter D and E
	Steel connections			Moment connections Shear connections	AISC 360-10 Chapter J
System 2	Steel beams	• Moment	• Hinge rotation	• Shear	ASCE 41-13, Table 9-6
	Steel columns	• PMM	• Hinge rotation	• Shear	ASCE 41-13, Table 9-6
	Footing	-	-	Bearing capacity of soil Flexural, shear	ACI 318-08 Chapter 15
	Steel truss			Compression	AISC 360-10

[3] Masonry infill walls shall be provided with horizontal reinforced concrete (RC) bands through the wall at about one-third and two-thirds of their height above the floor in each storey. Wall openings shall be framed by RC framing components as per NBC 201:1994 Clause 8.

Structural System	Component	Deformation-Controlled		Force-Controlled	Reference
		Action	NL Response	Action	
				• Flexural buckling • Torsional and flexural-torsional buckling Tension	Chapter D and E
	Steel connections			Moment connections Shear connections	AISC 360-10 Chapter J
System 3	Reinforced interlocking bearing walls	• In-plane flexure and shear	• Drift	• Axial compression	ASCE 41-13, Table 11-7 as appropriate and test results
	Footing	-	-	Bearing capacity of soil Flexural, shear	ACI 318-08 Chapter 15
	Steel truss			Compression • Flexural buckling • Torsional and flexural-torsional buckling Tension	AISC 360-10 Chapter D and E
	Steel connections			Moment connections Shear connections	AISC 360-10 Chapter J
System 4	RC beams	• Moment	• Hinge rotation	• Shear	ASCE 41-13, Table 10-7
	RC columns	• PMM	• Hinge rotation	• Axial compression • Shear	ASCE 41-13, Table 10-8
	Footing	-	-	Bearing capacity of soil Flexural, shear	ACI 318-08 Chapter 15
	Steel truss			Compression • Flexural buckling • Torsional and flexural-	AISC 360-10 Chapter D and E

Structural System	Component	Deformation-Controlled		Force-Controlled	Reference
		Action	NL Response	Action	
				torsional buckling Tension	
	Steel connections			Moment connections Shear connections	AISC 360-10 Chapter J
System 5	Cold-formed Steel beams			• Moment, Shear	AISI-Commentary Chapter C
	Cold-formed Steel columns			• Axial, moment, Shear	AISI-Commentary Chapter C
	Footing	-	-	Bearing capacity of soil Flexural, shear	ACI 318-08 Chapter 15
	Cold-formed Steel truss			Compression Tension	AISI-Commentary Chapter C
	Steel connections			Moment connections Shear connections	AISC 360-10 Chapter J
System 6	Hot-rolled steel beams	Moment	Hinge rotation	Shear	ASCE 41-13, Table 9-6
	Hot-rolled steel columns	PMM	Hinge rotation	Shear	ASCE 41-13, Table 9-6
	Footing	-	-	Bearing capacity of soil Flexural, shear	ACI 318-08 Chapter 15
	Steel truss			Compression • Flexural buckling • Torsional and flexural-torsional buckling Tension	AISC 360-10 Chapter D and E
	Steel connections			Moment connections Shear connections	AISC 360-10 Chapter J
System 7	Not applicable				

7.4.3 Performance Criteria for Design Procedure 2

The ductility factor: “μ”, is determined by the ratio between the maximum displacement and the displacement at first yield.

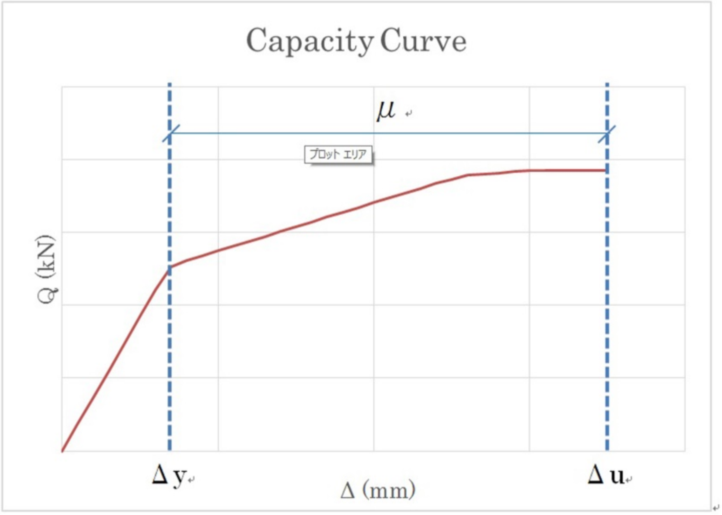

Figure 7-1 : Capacity Curve from Pushover Analysis

Response reduction factor, R, shall be determined from following equations as below.

R = μ (for structural periods greater than approximately 0.7 sec)

R = $\sqrt{2\mu - 1}$ (for structural periods less than approximately 0.3 sec)

If R factor in code-based design is less than R factor determined from performance-based evaluation, code-based design will be carried out using R factor from performance-based evaluation.

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