Remarks regarding FEMA 368 seismic analysis guidelines

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Abstract

The intent of this paper is to explore the recommendations of FEMA 368 on seismic analysis of buildings from a structural engineers' perspective. The objectives are to: 1) illustrate the decision making process on the selection of a seismic analysis method in FEMA 368, 2) present a clear sequence of steps that will guide a structural engineer using FEMA 368 guidelines to determine the appropriate analysis method by calculating the appropriate quantities as they are needed, and 3) compare the response history analysis procedure to the equivalent lateral force procedure permitted in the body of FEMA 368 guidelines.
Keywords: dynamic analysis, equivalent lateral force, response history analysis, story drift, FEMA368.

1 Introduction

FEMA 368 is created with the sponsorship of the Federal Emergency Management Agency (FEMA). The purpose of this document is to provide guidance for the engineering community on the seismic resistant design of structures. FEMA publishes updated recommendations on seismic analysis and design every three years. It includes recommendations for structural and nonstructural building components. In the year 2000, the National Institute of Building Systems (NIBS) updated the *Provisions* for FEMA and the resulting document is FEMA 368. The complete title of the document is *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*. Presidential Executive Order 12699 mandates that all federal buildings be constructed to mitigate seismic hazard and that NEHRP Provisions are considered to be the suitable design standard [4]. Analysis and design recommendations for certain engineering materials, structural components, and non-structural components are distributed in 14 chapters and two appendices. This presentation provides a clear understanding of the decision making process that leads to the selection of an appropriate seismic analysis method and discusses some of the important seismic analysis provisions. In this paper, the term *provisions* will be used to mean FEMA 368 guidelines.

2 Seismic analysis procedures

This section provides important decision making guidance and analysis steps that are readably useable by a structural engineer interested in implementing the *provisions*. At the end of this section, four of the analysis methods permitted by FEMA 368 are discussed and compared.

2.1 The first perquisite analysis step

Before an analysis procedure, such as the Equivalent Lateral Force (ELF) method or Modal Response Spectrum analysis method can be selected as the appropriate method, the structure will have to meet certain conditions to ensure reliable results. These conditions will be explained in a subsequent section. A mandatory first step to qualify a structure for a certain analysis method is to determine the *Seismic Design Category* of the Structure. These categories are designated A, B, C, or D. The steps to determine the seismic design category are:

1. Use seismic maps 1 to 24 to determine the *mapped maximum considered earthquake spectral response acceleration* at short period S_s and at 1 second S_1 (section 4.1.2 of *the provisions*), for the specific site under consideration.
2. Determine the Site Class (A, B, C, D, E, or F) using sections 4.1.2.1 through sections 4.1.2.3 of *the provisions*. Site class describes the local soil conditions. Class A represents hard rock and Class F represents soils requiring site-specific evaluations.
3. Use the *Mapped Maximum Considered Earthquake Spectral Response Acceleration* obtained in step 1 and the *Site Class* in step 2 and enter *provision* Tables 4.1.2.4a and 4.1.2.4b to determine the site coefficients F_a and F_v, respectively. F_a adjusts short period spectral acceleration for site conditions while F_v adjusts the 1-second spectral acceleration for site conditions.
4. Calculate the *Maximum Considered Earthquake Spectral Response Acceleration* for short period, $\boldsymbol{S_{MS}}$, and at 1 second, S_{M1}.

$$S_{MS} = F_a S_s. \tag{1}$$

$$S_{M1} = F_v S_1. \tag{2}$$

5. Calculate the *Design Earthquake Spectral Response Acceleration* at short period S_{DS} and at 1 second, S_{D1}.

$$S_{DS} = \frac{2}{3} S_{MS}. \tag{3}$$

$$S_{D1} = \frac{2}{3} S_{M1}. \tag{4}$$

6. Determine the *Seismic Use Group* of the structure (i.e. group I, II, or III) described in *provisions* section 1.3 and summarized below.
   - Seismic Use Group III: Essential facilities that are required for post-earthquake recovery and those containing substantial quantities of hazardous substances.
   - Seismic Use Group II: Structures that have a substantial public hazard due to occupancy or use.
   - Seismic Use Group I: Structures that are not included in seismic groups II and III.

   Knowing the seismic use group, determine the importance factor, I, from *provisions* Table 1.4. The importance factor will be used in seismic analysis using the ELF method. The seismic use group also affects the maximum permissible story drift as described in a subsequent section.
7. *Determine the Seismic Design Category* A, B, C, or D from Table 4.2.1a and Table 4.2.1b using the value of S_{DS} calculated in step 5 above and the *Seismic Use Group* determined in step 6.

Seismic Design Category determined in this step is used in subsequent sections to determine the method of seismic analysis permitted by FEMA 368.

2.2 The second perquisite analysis step

After the *Seismic Design Category* is determined from the previous section, a structural analysis procedure is to be selected. The type of analysis procedure permitted depends on the *Seismic Design Category,* the amount of plan or vertical irregularity present in the structure, and the quantity $T_s = \frac{S_{D1}}{S_{DS}}$. T_s is the ratio of *Design Earthquake Spectral Response Acceleration* at 1 second to short period. *Provisions* Table 5.2.3.2 describes the types of plan structural irregularities and Table 5.2.3.3 describes the type of vertical irregularities. Depending of the severity of the plan and/or vertical building irregularities, a complete response history analysis may be required.

2.3 Load combinations and analysis procedures

The analysis load combinations to design structures in regions where seismic design is necessary are the same as the ASCE 7-02 [5] combinations. ASCE 7-02 load combinations that include seismic forces are combinations 5 and 7 listed below:

$$1.2D + 1.0E + L + 0.2S. \tag{5}$$

$$0.9D + 1.0E + 1.6H. \tag{6}$$

Earthquake loads E listed in combinations 5 and 7 above are calculated from provision 5.2.7 as follows:
a. For the situation where gravity loads are seismic loads are additive

$$E = \rho Q_E + 0.2 S_{DS} D. \tag{7}$$

b. When gravity load counteracts seismic load, seismic load effect is computed using the following equation

$$E = \rho Q_E - 0.2 S_{DS} D. \tag{8}$$

Seismic force effect Q_E is obtained from structural analysis using procedures that depend on Seismic Design Category, structural system, dynamic properties, and regularity of the structure. The provisions for seismic analysis are included in Chapter 5 of *the provisions*.

Index Force Analysis method is the simplest of all methods described in *the provisions*. However, the method is limited to structures in Seismic Design Category A, which is a severe restriction to the method. The ELF method is also relatively simple but is applicable to a wider range of structures except when the structure has certain types of plan and vertical irregularities. However, even for structures where the use of ELF methods is not permitted for final design, ELF will generally be used to estimate certain response characteristics before other more general methods can be used.

2.3.1 Equivalent lateral force analysis

This method of analysis is not suitable for building with certain types of plan and vertical irregularities. However, it is an essential first step for other more general analysis methods. Before calculations related to the ELF method are performed, the short period design spectral acceleration, S_{DS} , and importance factor, I , need to be determined.

1. Calculate the total seismic shear section 5.4, FEMA368 [1]

$$V = C_s W. \tag{9}$$

   a. Calculate the *seismic response coefficient* (*Provisions* eqn (5.4.1.1-2)).

$$C_s = \frac{S_{DS}}{R/I}. \tag{10}$$

   Calculate the minimum seismic response coefficient (FEMA 368 Equation 5.4.1.1-3)

$$C_{s,\min} = 0.044 I S_{DS}. \tag{11}$$

   Calculate the maximum seismic response coefficient

$$C_{s,\max} = \frac{S_{D1}}{T(R/I)}. \tag{12}$$

   If $C_s < C_{s,\min}$ use $C_s = C_{s,\min}$

   If $C_s > C_{s,\max}$, use $C_s = C_{s,\max}$

   b. Calculate the load W
   All of the dead loads (weights of slabs, beams, columns, etc)

+ 25% of floor live load in storage areas (if any). Do not include garages.
+ actual weight of partitions but not less than 10 psf (500 Pa/sq.m). This is considered when an allowance for partition load is included in the floor load design
+ weight of permanent equipment (not accounted for in other places)
+ snow loads on flat roofs when estimated load is greater than 30 psf.

2. Calculate the approximate fundamental period.

$$T_a = C_r h_n^x. \tag{13}$$

h_n^x = height (ft or m) above the base to the highest level of the structure.

C_r and x: constants from *provisions* Table 5.4.2.1. They depend on structure type (steel or concrete, amount of seismic force carried by moment resisting frames, etc.

OR

If a *moment resisting frame* concrete or steel structure does not exceed 12 stories in height and story heights are at least 10 ft (3m), the fundamental period can be calculated from

$$T_a = 0.1N. \tag{14}$$

N = Number of stories

3. Distribute the total shear force V (kip or kN) to determine the lateral force at each floor level.

$$F_x = C_{vx}V. \tag{15}$$

$$C_{vx} = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k}.$$

w_i and w_x : portion of the total gravity load, W , located or assigned to level, i , or x

h_i and h_x : height (ft or m) from the base to level i or x .

k : an exponent related to the structure period.
= 1.0 (for structures having a period less than or equal to 0.5 seconds)
= 2.0 (for structures having a period greater than or equal to 2.5 seconds)
= 2.0 (for structures having a period between 0.5 and 2.5 seconds). Linear interpolation is also permitted.

4. Calculate the horizontal shear distribution at each story level.
Calculate the seismic design story shear force V_x (kip or kN) at each story level x using,

$$V_x = \sum_{i=x}^{n} F_i. \tag{16}$$

The seismic story shear force, V_x, should then be distributed to vertical elements of the seismic-force-resisting system in the story under consideration based on the relative lateral stiffnesses of the vertical-resisting elements and the diaphragm.

5. Calculate the overturning moment at each floor level, x, due to all forces, F_i, between the base and the floor level under consideration.

$$M_x = \sum_{i=1}^{n} F_i \left(h_i - h_x\right). \tag{17}$$

F_i: portion of the seismic base shear, V_x, induced at level, i.

h_i and h_x : the height (ft or m) from the base to Level i or x

n : number of levels above the story under consideration.

The foundation can be designed for 75% of the foundation overturning moment (kip.ft or kN.m).

Structural engineers should note that when Equation 11 (*Provisions* eqn (5.4.1.1-3)) above controls the calculation of the *seismic response coefficient*, C_s, that equation should not be used to calculate drifts. The intent of FEMA 368 is that drifts should be calculated using eqn (10) (*provisions* eqn (5.4.1.1-3)), which provides realistic values. To minimize analysis time, forces can be calculated using eqn (11) but drifts obtained from that analysis should be scaled up by the factor $\dfrac{C_s}{C_{s_{\min}}}$.

The use of the relatively simple ELF method is permitted for analysis and final design of structures that meet certain conditions as described in Fig. 1. However, the capabilities of today's software and computers make the use of more refined methods, such as the modal response spectrum more realistic.

2.4 Choice of seismic analysis method

Once the Seismic Design Category is determined, an approximate fundamental period and the quantity T_s are calculated, the engineer is ready to select an appropriate analysis method. The restrictions on using each of the analysis methods are detailed in Chapter 5 of *the provision*. Fig. 1 is a flowchart that can guide the decision-making process to select the appropriate seismic analysis method. Analysis method selected based on Fig. 1 satisfies the requirements of *provisions* section 5.2.5.

The linear response spectrum analysis method is considered more refined than the ELF method. However, compared to the modal response spectrum analysis method, linear response spectrum analysis method is more demanding, especially when it comes to the preparation of analysis model and the selection of suitable set of ground motions.

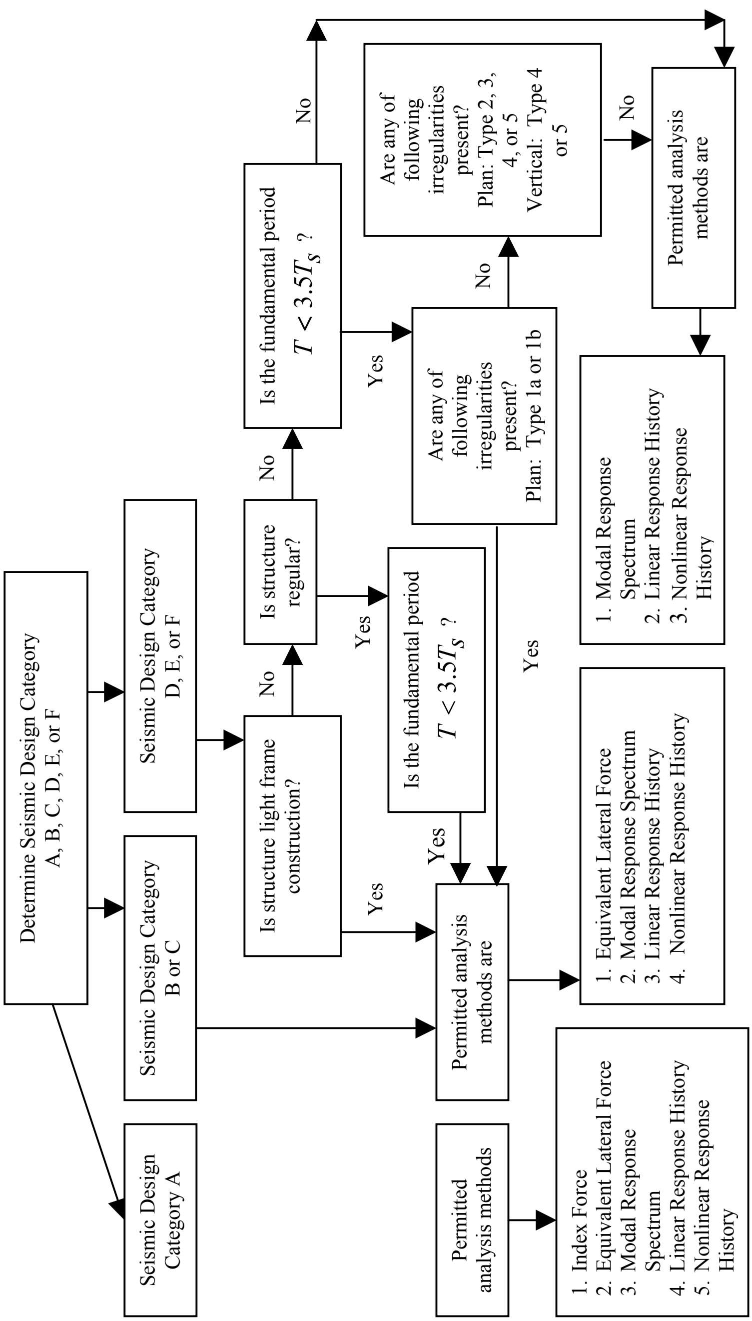

Figure 1: Decision making guide for choice of a seismic analysis procedure that satisfies the requirements of Chapter 5 of FEMA 368.

The nonlinear response spectrum analysis method is the most promising of all methods shown in Fig. 1 and provides the designer with valuable information. The continuing improvement in software capabilities and personal computers will make the method more appealing. However, most codes and standards including FEMA 368 do not clearly address important issues related to the selection of ground motions needed for this type of analysis [6]. Furthermore, creation of a suitable model and interpretation of results from a nonlinear dynamic analysis requires special expertise. Nonetheless, all structures that can be designed in accordance with FEMA 368 can be analyzed using modal response spectrum and linear response history analysis methods. This makes nonlinear response history analysis optional.

2.4.1 Insights on the analysis and design philosophy in FEMA 368

FEMA 368 permits linear elastic analysis for all structures even though, in high seismicity regions, ground shaking may produce forces and deformations much greater the yield limits. The design earthquakes, which may cause structures to deform beyond their yield limit, are scaled down by the response modification factor, R, which appears in eqns (10) and (12). Structures designed for this reduced design lateral force are expected to perform satisfactorily if: 1) the selected structure is suitable, 2) the detailing provides appropriate level of ductility, and 3) structures are not highly irregular [4]. Observations on performance of buildings during past earthquakes confirm the conclusion above. One of the reasons for satisfactory performance is that fundamental periods tends to increase during inelastic deformations which results in a reduction in strength demand [4].

2.5 Drift

After a seismic analysis is completed based on a method selected in the previous section, maximum story drift become available. Story drift at any level should not exceed a maximum allowable story drift Δ_a. *Provisions* Table 5.2.8 lists the limiting values of story drift for structures analyzed using linear methods such as the ELF method. The limiting story drift depends on the seismic use group, the material and type of structure, and height. For example, the limiting deflection for a masonry cantilever shear wall in a structure that falls in seismic use group II is $0.01h_{sx}$.

The *provisions* require that the story drifts due to seismic forces shall be obtained from structural analysis that accounts for cracked section effects on the stiffness of reinforced concrete and masonry elements.

A particularly important consideration in FEMA 368 is section 5.2.2.4.3, which requires structural elements that are not part of the lateral force resisting force system to resist moments and shears caused by seismic story drifts, Δ. This is because such elements may still experience lateral deformations and forces as the lateral force resisting system deforms. Observations on performance of buildings during the 1994 Northridge earthquake show that some buildings have partially collapsed due to poorly detailed structural elements that are not part of the lateral force resisting system [4].

2.6 Special analysis provisions for time history and response spectrum analysis

When the analysis is performed using Response Spectrum, section 5.5.7 of *the provisions* requires design forces, as well as drifts, to be scaled to values consistent with 85 of the values calculated using the ELF method with a base shear computed using a fundamental period equals to $C_u T_a = 2.23$ seconds.

When Response History Analysis is used, section 5.6.3 of the provisions requires the Response History Forces to be scaled up to the values consistent with ELF analysis with base shear computed using a period $C_u T_a = 2.23$. This requirement is considered unclear because this method is more reliable than ELF

3 Conclusions

Some of the basic provisions for seismic analysis and design using FEMA 368 were examined and discussed. A flowchart was produced that can aid a structural engineer in the selection of appropriate analysis method while observing restrictions on analysis methods imposed by *the provisions*.
The following observations on the FEMA 368 were made:

- The structural analysis method permitted by FEMA 368 depends on the *Seismic Design Category*, plan and vertical irregularities of the building, fundamental period, and the ratio of the Design Earthquake Spectral Acceleration Response at 1 second to short period acceleration $T_s = \frac{S_{D1}}{S_{DS}}$. However, the provisions permit three methods to be used regardless of *Seismic Design Category*, fundamental period, plan or vertical irregularity, or $T_s = \frac{S_{D1}}{S_{DS}}$. The three methods are:
    - Modal Response Spectrum Analysis
    - Linear Response History Analysis, and
    - Nonlinear Response History Analysis.
- The *Response History Analysis* method is considered the most general for seismic structural analysis. The commentary of the provisions considers the method as one that requires special expertise and recommends caution when interpreting the results. Section 5.6.3 of *the provisions* requires that seismic forces calculated using Response History Analysis method be scaled up to forces obtained to forces obtained from the ELF method with base shear computed using $T = C_u T_a$.

- The *Provisions* adopt linear elastic analysis of structures and emphasizes ductility and continuity of lateral force resisting systems as important design and detailing requirements.
- The *Provisions* require structural elements that are not part of the lateral force resisting system to be designed for the additional moments and deformations caused by deformation of lateral force resisting system. This will guard against collapses observed in previous earthquakes.

References

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