Seismic Analysis Using Three Dimensional Modeling

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Abstract

Three-dimensional dynamic analysis is required for a large number of different types of structural systems that are constructed in Seismic Zones. The lateral force requirements suggest several methods that can be used to estimate the distribution of seismic forces within a structure. However, these guidelines are not unique and need further interpretations. The major advantage of using the forces obtained from a dynamic analysis as the basis for a structural design is that the vertical distribution of forces may significantly be different from the forces obtained from an equivalent static load analysis.

التحليل الزلزالي بأستخدام نموذج ثلاثي الابعاد

الخلاصة

التحليل الحركي ثلاثي الأبعاد يعتبرمطلوبا لعدد كبير من الأنواع المختلفة للأنظمةِ الهيكليةِ المشيدة في المناطق الزلزاليةِ. لتحقيق متطلباتُ القوةِ الجانبيةِ يتم اقتراح عدّة طرق لتخمين توزيع القوى الزلزاليةِ ضمن هذة الهياكل لانشائية. ان الفائدة الرئيسية لإستعمال القوى الناتجة مِنْ التحليل الحركي هي الاساس في التصميم الانشائي. أنّ التوزيع العمودي للقوى قدْ يَكُون مختلف بشكل ملحوظ عن القوى الناتجة مِنْ تحليلِ حملِ ساكن مكافئ.

Notations

C = Numerical coefficient (C = 1.25 S/ $T^{2/3}$), Cmax= 2.75[1].

Ct = Defined by code for various types of structural systems [1].

h = Height of the structure (meter).

I = Importance factor [1].

RW = Numerical coefficient for building characteristics [1].

S = Site coefficient for soil characteristics.

T = Fundamental period of vibration (seconds).

V =Base shear (kN).

W = Total seismic weight of the structure (kN).

Z = Seismic zone factor [1].

Introduction

Dynamic analysis will produce structural designs that are more earthquake resistant than structures designed using static loads. For many years, approximate two-dimensional static load was acceptable as the basis for seismic design in many geographical areas and for most types of structural systems. During the past twenty years, due to the increasing availability of modern digital computers, most engineers have had experience with the static load analysis of three dimensional structures. However, few engineers, and the writers of the current uniform building code[1], have had experience with the

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three dimensional dynamic response analysis. Therefore, the interpretation of the dynamic analysis requirement of the current uniform building code represents a new challenge to most structural engineers.

The current code allows the results obtained from a dynamic analysis to be normalized so that the maximum dynamic base shear is equal to the base shear obtained using a simple two-dimensional static load analysis. Most members of the profession realize that there is no theoretical foundation for this approach. However, for the purpose of selecting the magnitude of the dynamic loading that will satisfy the code requirements. This approach can be accepted in a modified form, until a more rational method is adopted. The calculation of the "design base shears" is simple and the variables are defined in the current uniform building code[1].

It is of interest to note, however, that the basic magnitude of the seismic loads has not significantly changed from previous codes. The major change is that "dynamic methods of analysis" must be used in the "principal directions" of the structure. The present code does not state how to define the principal directions for a three dimensional structure of arbitrary geometric shape. Since the design base shear can be different in each direction, this "scaled spectra" approach can produce a different input motion for each direction, for both regular and irregular structures. Therefore, the current code dynamic analysis approach can result in a structural design which is relatively "weak" in one direction[2,3].

In addition, the maximum possible design base shear, which is defined by the present uniform building code[1], is approximately 35 percent of the weight of the structure. For many structures, it is less than 10 percent. It is generally recognized that this force level is small when compared to measured earthquake forces. Therefore, the use of this design base shear requires that substantial ductility be designed into the structure.

The definition of an irregular structure, the scaling of the dynamic base shears to the static base shears for each direction, the application of accidental torsional loads and the treatment of orthogonal loading effects are areas which are not clearly defined in the current building code. The purpose of this paper is to present one method of three dimensional seismic analyses that will satisfy the Lateral Force Requirements of the uniform building code. The method is based on the response spectral shapes defined in the code and previously published and accepted computational procedures[4,5].

2. Dynamic Analysis:-

It is possible to conduct a dynamic, time-history, response analysis by either the mode superposition or step-by-step methods of analysis. However, a standard time history ground motion, for the purpose of design, has not been defined. Therefore, most engineers use the response spectrum method of analysis as the basic approach. The first step in a response spectrum analysis is the calculation of the three dimensional mode shapes and frequencies as indicated in the previous section.

2.1. Response Spectrum Analysis:-

This approach permits the multiple modes of response of a building to be taken into account (in the frequency domain). This is required in many building codes for all structures except for very simple or very complex structures. The response of a structure can be defined as a combination of

many special shapes (modes) that in a vibrating string correspond to the "harmonics". Computer analysis can be used to determine these modes for a structure. For each mode, a response is read from the design spectrum, based on the modal frequency and the modal mass, and they are then combined to provide an estimate of the total response of the structure. Combination methods include the following[2]:

. Absolute - peak values are added together

. Square root of the sum of the squares (SRSS)

. Complete quadratic combination (CQC) - a method that is an improvement on SRSS for closely spaced modes

It should be noted that the result of a response spectrum analysis using the response spectrum obtained from a ground motion is typically different from that which would be calculated directly from a linear dynamic analysis using that ground motion directly, since phase information is lost in the process of generating the response spectrum.

In cases where structures are either too irregular, too tall or of significance to a community in disaster response, the response spectrum approach is no longer appropriate, and more complex analysis is often required, such as non-linear static or dynamic analysis[3].

2.2. Linear Dynamic Analysis:-

Static procedures are appropriate when higher mode effects are not significant. This is generally true for short, regular buildings. Therefore, for tall buildings, buildings with tensional irregularities, or non-orthogonal systems, a dynamic procedure is required. In the linear dynamic procedure, the building is modeled as a multi-degree-of-freedom (MDOF) system with a linear elastic stiffness matrix and an equivalent viscous damping matrix[6].

The seismic input is modeled using either modal spectral analysis or time history analysis but in both cases, the corresponding internal forces and displacements are determined using linear elastic analysis. The advantage of these linear dynamic procedures with respect to linear static procedures is that higher modes can be considered. However, they are based on linear elastic response and hence the applicability decreases with increasing nonlinear behavior, which is approximated by global force reduction factors.

In linear dynamic analysis, the response of the structure to ground motion is calculated in the time domain, and all phase information is therefore maintained. Only linear properties are assumed. The analytical method can use modal decomposition to reduce the degrees of freedom in the analysis[7].

2.3. Non-linear Static Analysis

In general, linear procedures are applicable when the structure is expected to remain nearly elastic for the level of ground motion or when the design results in nearly uniform distribution of nonlinear response throughout the structure. As the performance objective of the structure implies greater inelastic demands, the uncertainty with linear procedures increases to a point that requires a high level of conservatism in demand assumptions and acceptability criteria to avoid unintended performance. Therefore, procedures incorporating inelastic analysis can reduce the uncertainty and conservatism[8].

This approach is also known as "pushover" analysis. A pattern of forces is applied to a structural model that

includes non-linear properties (such as steel yield), and the total force is plotted against a reference displacement to define a capacity curve. This can then be combined with a demand curve (typically in the form of an acceleration-displacement response spectrum (ADRS)). This essentially reduces the problem to a single degree of freedom system.

Nonlinear static procedures use equivalent SDOF structural models and represent seismic ground motion with response spectra. Story drifts and component actions are related subsequently to the global demand parameter by the pushover or capacity curves that are the basis of the non-linear static procedures [9].

2.4. Non-linear Dynamic Analysis

Nonlinear dynamic analysis utilizes the combination of ground motion records with a detailed structural model, therefore is capable of producing results with relatively low uncertainty. In nonlinear dynamic analyses, the detailed structural model subjected to a ground-motion record produces estimates of component deformations for each degree of freedom in the model and the modal responses are combined using schemes such as the square-root-sum-of-squares.

In non-linear dynamic analysis, the non-linear properties of the structure are considered as part of a time domain analysis. This approach is the most rigorous, and is required by some building codes for buildings of unusual configuration or of special importance. However, the calculated response can be very sensitive to the characteristics of the individual ground motion used as seismic input; therefore, several analyses are required using different ground motion records [10].

2.5. Three Dimensional Computer Model

Real and accidental torsional effects must be considered for all structures. Therefore, all structures must be treated as three dimensional systems. Structures with irregular plans, vertical setbacks or soft stories will cause no additional problems if a realistic three dimensional computer model is created. This model should be developed in the very early stages of design since it can be used for static wind and vertical loads, as well as dynamic seismic loads. Only structural elements with significant stiffness and ductility should be modeled. Non-structural brittle components can be neglected. However, shearing, axial deformations and non-center line dimensions can be considered in all members without a significant increase in computational effort by using finite element model, implemented by computer software (STAAD/Pro-2006 computer program) [5]. The rigid, in-plane approximation of floor systems has been shown to be acceptable for most buildings. For the purpose of elastic dynamic analysis, gross concrete sections, neglecting the stiffness of the steel, are normally used. A cracked section mode should be used to check the final design. The effect of including P-Delta displacements in a dynamic analysis results in a small increase in the period of all modes. In addition to being more accurate, an additional advantage of automatically including P-Delta effects is that the moment magnification factor for all members can be taken as unity in all subsequent stress checks [5].

The mass of the structure can be estimated with a high degree of accuracy. The major assumption

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required is to estimate the amount of live load to be included as added mass. For certain types of structures it may be necessary to conduct several analyses with different values of mass. The lumped mass approximation has proven to be accurate. In the case of the rigid diaphragm approximation, the rotational mass moment of inertia must be calculated [5].

The computer model for static loads should only be executed prior to conducting a dynamic analysis. Equilibrium can be checked and various modeling approximations can be verified with simple static load patterns. The results of a dynamic analysis are generally very complex and the forces obtained from a response spectra analysis are always positive. Therefore, dynamic equilibrium is almost impossible to check. However, it is relatively simple to check energy balances in both linear and nonlinear analysis [5].

3. Three Dimensional Mode Shapes And Frequencies

The first step in the dynamic analysis of a structural model is the calculation of the three dimensional mode shapes and natural frequencies of vibration. Within the past several years, very efficient computational methods have been developed which have greatly decreased the computational requirements associated with the calculation of orthogonal shape functions

In order to illustrate the dynamic properties of the three dimensional structure, the mode shapes and frequencies are calculated for the irregular, eight stories, 24 meter tall building shown in Figure [1]. This building is a reinforcement concrete structure with several hundred degrees-

of-freedom. However, the three components of mass are lumped at each of the eight floor levels. Therefore, only 24 three dimensional mode shapes are possible.
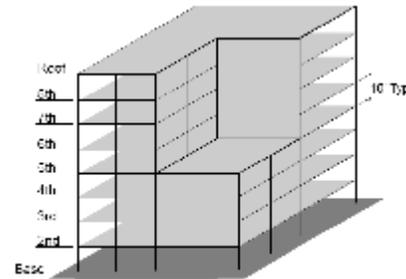
Light Story Irregular Building

Each three dimensional mode shape of a structure may have displacement components in all directions. For the special case of a symmetrical structure, the mode shapes are uncoupled and will have displacement in one direction only. Since each mode can be considered to be a deflection due to a set of static loads, six base reaction forces can be calculated for each mode shape [11].

The two base reactions and three overturning moments associated with each mode shape. Since vertical mass has been neglected there is no vertical reaction. The magnitudes of the forces and moments have no meaning since the amplitude of a mode shape can be normalized to any value. However, the relative values of the different components of the shears and moments associated with each mode are of considerable value. The modes with a large tensional component are highlighted in bold.

The three dimensional mode shapes at the early stages of a preliminary design. The structural engineer can provide with additional information which can be used to improve the earthquake

resistant design of a structure. The current uniform building code[1] defines an "irregular structure" as one which has a certain geometric shape or in which stiffness and mass discontinuities exist. A far more rational definition is that a "regular structure" is one in which there is a minimum coupling between the lateral displacements and the torsional rotations for the mode shapes associated with the lower frequencies of the system. Therefore, if the model is modified and "tuned" by studying the three dimensional mode shapes during the preliminary design phase, it may be possible to convert a "geometrically irregular" structure to a "dynamically regular" structure from an earthquake resistant design standpoint[1].

For this building, it is of interest to note that the mode shapes, which tend to have directions that are 90 degrees apart, have almost the same value for their period. This is typical of three dimensional mode shapes for both regular and irregular buildings. For regular symmetric structures, which have equal stiffness in all directions, the periods associated with the lateral displacements will result in pairs of identical periods. However, the directions associated with the pair of three dimensional mode shapes are not mathematically unique the square root of the sum of the squares (SRSS) method should not be used to combine modal maximums in three dimensional dynamic analysis. The complete quadratic combination (CQC) method eliminates problems associated with closely spaced periods.

For a response spectrum analysis, the current uniform building code states that "at least 90 percent of the participating mass of the structure must be included in the calculation of response for each principal direction." Therefore, the number of modes to be evaluated must satisfy this requirement [13].

4. Equivalent Static Analysis

This approach defines a series of forces acting on a building to represent the effect of earthquake ground motion, typically defined by a seismic design response spectrum. It assumes that the building responds in its fundamental mode. For this to be true, the building must be low-rise and must not twist significantly when the ground moves. The response is read from a design response spectrum, given the natural frequency of the building (either calculated or defined by the uniform building code). The applicability of this method is extended in many building codes by applying factors to account for higher buildings with some higher modes, and for low levels of twisting. To account for effects due to "yielding" of the structure, many codes apply modification factors that reduce the design forces (e.g. force reduction factors)[7].

5. Response Spectrum Analysis

This approach permits the multiple modes of response of a building to be taken into account (in the frequency domain). This is required in many building codes for all except for very simple or very complex structures. The response of a structure can be defined as a combination of many special shapes (modes) that in a vibrating string correspond to the "harmonics". Computer analysis can be used to determine these modes for a structure. For each mode, a response is read from the design spectrum, based on the modal frequency and the modal mass, and they are then combined to provide

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In cases where structures are either too irregular, too tall or of significance to a community in disaster response, the response spectrum approach is no longer appropriate, and more complex analysis is often required, such as non-linear static or dynamic analysis[9].

The possible tensional ground motion, the unpredictable distribution of live load mass and the variations of structural properties are three reasons why both regular and irregular structures must be designed for accidental tensional loads. Also, for a regular structure lateral loads do not excite tensional modes. One method suggested in the uniform building code is to conduct several different dynamic analyses with the mass at different locations. This approach is not practical since the basic dynamic properties of the structure (and the dynamic base shears) would be different for each analysis. In addition, the selection of the maximum member design forces

would be a monumental post-processing problem[10].

The current code allows the use of pure static tensional loads to predict the additional design forces caused by accidental torsion. The basic vertical distribution of lateral static loads is given by Code provision. The static tensional moment at a certain level is calculated by the multiplication of the static load at that level by 5 percent of the maximum dimension at that level. In this research it is recommended that these pure tensional static loads, applied at the center of mass at each level, be used as the basic approach to account for accidental tensional loads. This static tensional load is treated as a separate load condition so that it can be appropriately combined with the other static and dynamic loads[10].

6. Static Seismic Analysis

For dynamic analysis, the 1994 UBC[1] requires that the "design base shear", V, is to be evaluated from the following formula:

$$V = [Z I C / RW] W \qquad …. (1)$$
$$C = 1.25 S/ T^{2/3} \qquad …. (2)$$

The period, T, as follows:

$$T = Ct\ h^{3/4} \qquad …. (3)$$

To illustrate the base-shear scaling method recommended here, a static seismic analysis is conducted on the building shown in figure (1). The eight-story building has (3 meter) story heights. The seismic dead load is 53.6 kN for the top four stories and 81.8 kN for the lower four stories. For $I = 1$, $Z = 0.4$, $S = 1.0$, and $R_W = 6.0$, the max base shear force and overturning moment and periods in critical axis calculated by using Uniform Building Code shown in table (1).

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The normalized response spectra shape for soil type 1, which is defined in the Uniform Building Code, is used as the basic loading for the three dimensional dynamic analyses. Using eight modes only and the square root of the sum of the squares (SRSS) method of combining modal maxima, the base shears and overturning moments shown in table (2).

The 1-axis (in critical 49.64 angle) is in the direction of the seismic input and the 2-axis (in critical -62.36 angle) is normal to the direction of the loading. This clearly illustrates the major weakness of the SRSS method of modal combination shown in table (3).

The complete quadratic combination (CQC) method of modal combination eliminates problems associated with the square root of the sum of the squares (SRSS) method. Also, it clearly illustrates that the directions of 38.64 and -51.36 degrees are a good definition of the principal directions for this structure shown in table (4).

For this case, the input spectra scale factor of (3.5) should be used for all directions and is based on the fact that both the dynamic base shears and the dynamic overturning moments must not be less than the static code forces. This approach is clearly more conservative than the approach suggested by the current Uniform Building Code. It is apparent that the use of different scale factors for a design spectrum in the two different directions, as allowed by the code, results in a design that has a weak direction relative to the other principle direction.

7. Concluding Remarks

A dynamic analysis method is summarized that produces unique design displacements and member forces which will satisfy the current Uniform Building Code. It can be used for both regular and irregular structures. The major steps in the approach are as follows:

1. A three dimensional computer model must be created in which all significant structural elements are modeled. This model should be used in the early phases of design since it can be used for both static and dynamic loads.

2. The three dimensional mode shapes should be repeatedly evaluated during the design of the structure. The directional and tensional properties of the mode shapes can be used to improve the design. A well-designed structure should have a minimum amount of torsion in the mode shapes associated with the lower frequencies of the structure.

3. The direction of the base reaction of the mode shape associated with the fundamental frequency of the system is used to define the principal directions of the three dimensional structure.

4. Using the complete quadratic combination (CQC) method, the "dynamic base shears" are calculated in each principal direction due to 100 percent of the Normalized Spectra Shapes. Use the minimum value of the base shear in the principal directions to produce one.

5. A pure torsion static load condition is produced using the suggested vertical lateral load distribution defined in the uniform building code.

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Table (1) Base Shear Forces Using the UBC code

Period (sec)	Angle (deg)	Base Shear (kN)	Overturning Moment (kN.m)
0.701	49.64	63	3267.3
0.610	-62.36	63.2	3367.6

Table (2) Dynamic Base Forces using the square root of the sum of the squares (SRSS) Method

	BASE SHEARS		OVERTURNING MOMENTS	
Angle -deg	V1 (kN)	V2 (kN)	M1 (kN.m)	M2 (kN.m)
0	13.1	12.6	670.4	690.87
90	13.44	12.6	670.4	716.05
49.64	15.75	1.2	14.9	929.63
-62.36	18.86	1.2	14.9	1011.69

Table (3) Dynamic Base Forces using the complete quadratic combination (CQC) Method

	BASE SHEARS		OVERTURNING MOMENTS	
Angle -deg	V_1(kN)	V_2(kN)	M_1 (kN.m)	M_2 (kN. m)
0	17.56	4.58	270.23	925.36
90	17.85	4.58	270.23	944.02
49.64	17.50	0.045	0.76	931.88
-62.36	18.93	0.045	0.76	1012.36

Table (4) Normalized Base Forces in Principal Directions

	49.64 Degrees		-62.36 Degrees	
	V (kN)	M (kN. m)	V (kN)	M (kN. m)
Static Code Forces	63	3267.3	63.2	3367.6
Dynamic Design Forces Scaled by Base Shear 63/17.50= 3.5	63	3312.05	67.27	3598.02