13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1156

MULTI-COMPONENT SEISMIC ANALYSIS FOR IRREGULAR STRUCTURES

Xiao-An GAO[1], Xi-Yuan ZHOU[1,2] and Li Wang[2]

SUMMARY

In this article, the methods of multi-component seismic response analysis for curved bridges are systemically analyzed and compared. Because of the interaction between bending and torsion resulted from the irregular plane, the maximum seismic response of curved bridges would be correlative with the input angle of earthquake. The employable domain and limitation of SRSS3 method is well defined from the intensive study of CQC3 method and SRSS3 method. Meanwhile the theory fundamental and parameters of simplified methods are analyzed in this study. The seismic responses of curved bridges based on real earthquake response spectra and design spectra, are calculated in various ways. To verify the mode superposition methods of response spectra, the time history analyses of bridges subjected to real earthquake records and the artificial earthquake waves which are synthesized from design spectra are carried out. Example analyses have been used to compare the validity and accuracy of CQC3 and SRSS3. The results illustrate that CQC3 method is more accurate and suitable to seismic design of important bridges. It is worth pointing out that more conservative results from both the SRSS and percentage methods should be adopted in seismic design for normal bridges in order to simplify calculation in design and ensure the safety of bridges during earthquakes.

INTRODUCTION

The dynamic response characteristics of curved, multiple-span highway bridges are quite different from those of other structures. This fact became very evident during the San Fernando, California, earthquake of February 9, 1971, when numerous reinforced concrete bridges of this type suffered severe damages. Based on the San Fernando experience, extended attention has been given to the study of seismic effects on bridges. Mathematical modeling and non-linear seismic analysis procedures for long, multi-span, reinforced concrete bridge structures have been developed by Tseng and Penzien [1,2], which take into account the coupled inelastic behaviors of reinforced concrete columns and the non-linear discontinuous behaviors of expansion joints. In order to verify the validity of these mathematical models and analytical procedures, detailed model experiments using a shaking table were conducted by Williams and Godden [3, 4] to provide dynamic response data similar to prototype bridge behaviors. Finite element analyses of seismic response of curved girder bridges including the warping effect of the curved beam element with

[1] Institute of Earthquake Engineering, China Academy of Building Research.
[2] Beijing Laboratory of Earthquake Engineering and Structural Retrofit, Beijing University of Technology, China.

eight degrees of freedom were discussed by Guohao Li [5]. Desroches and Fenves [6] evaluated the earthquake response of a curved highway bridge. They built a three-dimensional calibrated bridge model to investigate and compare significant differences between uniform free-field and non-uniform input motion. Zureick [7] presented analysis and dynamic properties of horizontally curved steel I-Girders and remarked the lack of rigor in gathering all the information resulting from earlier researches into a global database, available for qualitative review and evaluation. In reference to an earlier publication, Heinere [8] and Maneetes [9] described a large amount of resources and efforts fed into the research of horizontally curved bridges. However it seems no essential progress attained in these references. The effects and discrimination of single support motion and multi-support motions on the responses of curved bridges usually becomes research key points. Furthermore the dynamic response characteristics of curved bridge superstructure are very complex and expansion joints have a profound influence on the dynamic responses. However these researches are mainly focused on time history analysis including mode superposition and step by step integration. They do not provide satisfactory practical guidelines in the modal superposition method based on design response spectra.

Penzien and Watabe [10] have shown that the translational components of ground motions can be resolved into two directions, i.e. major axis and intermediate principal axis perpendicular to the major axis. It is known that ground motion can act along any horizontal direction for its complexity and randomness. Furthermore the existence of a possible different direction of seismic incidence would lead to an increase of structural dynamic response, especially for the complex three-dimensional structures, such as non-rectangular buildings, curved bridges. Although in the seismic design of regular structures the directions of ground motion incidence are usually applied along the fixed structural reference axis. But the direction of the earthquake, which produces the maximum stresses, in a particular member or at a specified point, is variable.

The maximum structural responses associated to the most critical directions of ground seismic motions have been examined in several papers. Wilson [11] proposed a method to calculate the critical angle of structural response. However it is approximate. Smeby [12] developed an explicit formula to determine the critical angle for the case of two horizontal ground components, using random vibration theory. Wilson and Suharwardy [13] proposed a method to calculate the maximum response of structures to multi-component of ground motion. This paper raised a series discuss due to not appropriate using mode superposition method [14, 15]. Lopez and Torres [16] presented correct theoretical derivation and results which were consistent with reference [12] using mode superposition method. A method called Three Dimensional Complete Quadratic Combination (CQC3) proposed by Menun [17] aims to reach a more accurate determination of the maximum structural response to three orthogonal components of seismic motion, which properly accounts for the correlation of seismic components. Lopez [18] indicated that in the Menun' paper, the percentage rule (30% and 40%) and CQC3 method were compared incorrect, and found an exaggerated error. More attention should be paid to that the above researches provide more or less practical guidelines based on the mode superposition method, and the researches have not been tested and verified by the time history analysis yet.

In the view of seismic design, some seismic code [19] prescribe simplified method to analyze the maximum response of the structure suffered to multi-component ground motion. Code for seismic design of buildings (GBJ111-87) [20] in China proposed corresponding specified standard. Code for seismic design of bridges specifies that the engineer can simplify curved bridge to straight bridge in a certain range, without considering the complexity of the curved bridges.

In this paper, a typical model that can capture essential features of the earthquake behaviors of curved bridges is investigated. Meanwhile the methods of multi-component seismic analysis for curved bridges are systemically analyzed and compared. The seismic responses of a curved bridge are calculated in various ways based on real response spectrum and standard design spectrum. To verify these design spectra based methods, the real earthquake records and the artificial earthquake waves computed from standard design spectrum are applied for time history analysis. Some suggestions about the code method of multi-component seismic analysis for bridges are given.

RESPONSE SPECTRAL SUPERPOSITION METHOD OF STRUCTURES SUBJECTED TO MULTI-COMPONENT EARTHQUAKE MOTION

CQC3 method

Figure 1 illustrates the situation of a structure subjected to the simultaneous actions of two orthogonal horizontal ground accelerations in directions 1 and 2, and vertical ground acceleration in direction 3 or Z. The component forms an angle θ with the X-axis, X and Y are the reference axis of the structure. It is assumed that input ground motion is represented by a wide-band stationary process. Directions 1, 2 and 3 are the principal ground acceleration directions. Let R be the maximum dynamic response or peak response to the simultaneous actions of the three spectra, corresponding response parameters such as displacement, stress, force, etc. For component in direction 1 or 2, the peak modal response in the i-th mode of vibration, can be written as:

$$R_i^1 = R_i^{1x}\cos\theta + R_i^{1y}\sin\theta \tag{1}$$

$$R_i^2 = -R_i^{2x}\sin\theta + R_i^{2y}\cos\theta \tag{2}$$

where R_i^{1x}, R_i^{1y} are the peak modal responses calculated when the ground motion in direction 1 acts along the reference axis of the structure, X and Y, respectively. R_i^{2x}, R_i^{2y} are the peak modal responses calculated when the ground motion in direction 2 acts along the reference axis of the structure, X and Y, respectively.

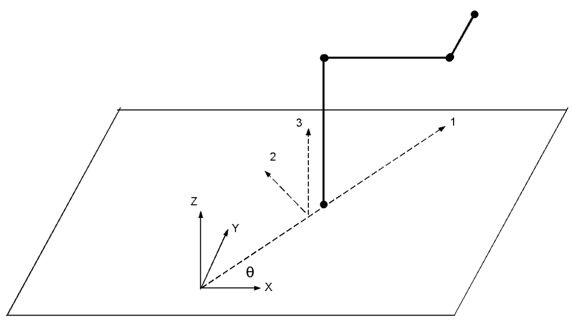


Figure 1 Structure subjected to two horizontal components applied along any arbitrary directions and the vertical component seismic motion

Using CQC method (Wilson [21]), the peak response R^1 is obtained by combining the peak modal responses including modal correlation to the seismic component 1. To seismic components 2 and 3, R^2 and R^3 are presented as follows:

$$R^1 = \left(\sum_i \sum_j C_{ij} R_i^1 R_j^1\right)^{1/2} \tag{3}$$

$$R^2 = \left(\sum_i \sum_j C_{ij} R_i^2 R_j^2\right)^{1/2} \tag{4}$$

$$R^3 = \left(\sum_i \sum_j C_{ij} R_i^3 R_j^3\right)^{1/2} \tag{5}$$

where C_{ij} is the correlation coefficient between responses in modes i and j . According to Chinese seismic design code, coefficient C_{ij} is:

$$C_{ij} = \frac{8\zeta_i\zeta_j\left(1+\frac{T_i}{T_j}\right)\left(\frac{T_i}{T_j}\right)^{1.5}}{\left(1-\left(\frac{T_i}{T_j}\right)^2\right)^2 + 4\zeta_i\zeta_j\left(1+\frac{T_i}{T_j}\right)^2\left(\frac{T_i}{T_j}\right)} \tag{6}$$

where T_i and T_j are the natural periods of mode i and j respectively. ζ_i and ζ_j are the damping ratios of modes i and j respectively.

Since ground components are uncorrelated, the peak response, R, to the simultaneous actions of the three components is given by:

$$R = \left(\left(R^1\right)^2 + \left(R^2\right)^2 + \left(R^3\right)^2\right)^{1/2} \tag{7}$$

From equations (1) ~ (6), the peak response R is obtained as a function of the angle of incidence θ：

$$\begin{aligned} R(\theta) = \Big\{ & \left[\left(R^{1x}\right)^2 + \left(R^{2y}\right)^2\right]\cos^2\theta + \left[\left(R^{1y}\right)^2 + \left(R^{2x}\right)^2\right]\sin^2\theta \\ & + 2\sin\theta\cos\theta\left[\sum_i\sum_j C_{ij}R_i^{1x}R_j^{1y} - \sum_i\sum_j C_{ij}R_i^{2x}R_j^{2y}\right] + \left(R^3\right)^2\Big\}^{\frac{1}{2}} \end{aligned} \tag{8}$$

where：

$$R^{1x} = \sum_i\sum_j C_{ij}R_i^{1x}R_j^{1x} \tag{9}$$

$$R^{1y} = \sum_i\sum_j C_{ij}R_i^{1y}R_j^{1y} \tag{10}$$

$$R^{2x} = \sum_i\sum_j C_{ij}R_i^{2x}R_j^{2x} \tag{11}$$

$$R^{2y} = \sum_i\sum_j C_{ij}R_i^{2y}R_j^{2y} \tag{12}$$

The critical angle, θ, is defined by the value that renders the maximum value of R in equation (8). Taking the derivative of R with respect to θ and setting it equal to zero, we get:

$$\theta = \frac{1}{2}\tan^{-1}\left\{\frac{2\left[\sum_i\sum_j C_{ij}R_i^{1x}R_j^{1y} - \sum_i\sum_j C_{ij}R_i^{2x}R_j^{2y}\right]}{\left(R^{1y}\right)^2 + \left(R^{2x}\right)^2 - \left(R^{1x}\right)^2 - \left(R^{2y}\right)^2}\right\} \tag{13}$$

Therefore, equation (13) gives two roots of θ, and the roots decide the maximum and the minimum values of the structural peak response R in equation (8).

Penzien and Watabe [10] have shown that the translational components of ground motions can be resolved into two directions, i.e. major axis and intermediate principal axis perpendicular to the major axis. Let us assume the following relationship between the horizontal spectra as $S_{a2} = \gamma S_{a1}$, where γ is defined as the spectral ratio for the horizontal components of ground motion. This assumption is usually adopted in the earthquake design of structures. The peak responses defined above are simplified as follows:

$$R^{2i} = \gamma R^{1i} \quad i = x, y \tag{14}$$

Substituting these expressions into equation (8), the peak response R is given as a function of the angle θ. Correspondingly θ is:

$$\begin{aligned} R(\theta) = \Big\{ & \left[\left(R^{1x}\right)^2 + \left(\gamma R^{1y}\right)^2 \right] \cos^2\theta + \left[\left(R^{1y}\right)^2 + \left(\gamma R^{1x}\right)^2 \right] \sin^2\theta \\ & + 2\sin\theta\cos\theta\left(1-\gamma^2\right)\left[\sum_i \sum_j C_{ij} R_i^{1x} R_j^{1y} \right] + \left(R^3\right)^2 \Big\}^{\frac{1}{2}} \end{aligned} \tag{15}$$

$$\theta = \frac{1}{2}\tan^{-1}\left\{ \frac{2\left[\sum_i \sum_j C_{ij} R_i^{1x} R_j^{1y} \right]}{\left(R^{1x}\right)^2 - \left(R^{1y}\right)^2} \right\} \tag{16}$$

From equation (16), if two components of ground motion are proportional, the critical angle is independency to the ratio γ. Equations (8) ~ (16) are named CQC3 method proposed by Menun [17].

SRSS3 method

If modal correlation coefficients of structure are small, SRSS method is used to be adopted as mode superposition method. Substituting equations (3) ~ (5) by equations:

$$R^1 = \left(\sum_i R_i^1 R_i^1 \right)^{1/2} \tag{17}$$

$$R^2 = \left(\sum_i R_i^2 R_i^2 \right)^{1/2} \tag{18}$$

$$R^3 = \left(\sum_i R_i^3 R_i^3 \right)^{1/2} \tag{19}$$

So equations (8) and (13) can be transformed to：

$$\begin{aligned} R(\theta) = \Big\{ & \left[\left(R^{1x}\right)^2 + \left(R^{2y}\right)^2 \right] \cos^2\theta + \left[\left(R^{1y}\right)^2 + \left(R^{2x}\right)^2 \right] \sin^2\theta \\ & + 2\sin\theta\cos\theta\left[\sum_i R_i^{1x} R_i^{1y} - \sum_i R_i^{2x} R_i^{2y} \right] + \left(R^3\right)^2 \Big\}^{\frac{1}{2}} \end{aligned} \tag{20}$$

where：

$$R^{1x} = \sum_i R_i^{1x} R_i^{1x} \tag{21}$$

$$R^{1y} = \sum_i R_i^{1y} R_i^{1y} \tag{22}$$

$$R^{2x}=\sum_i R_i^{2x}R_i^{2x} \tag{23}$$

$$R^{2y}=\sum_i R_i^{2y}R_i^{2y} \tag{24}$$

$$\theta=\frac{1}{2}\tan^{-1}\left\{\frac{2\left[\sum_i R_i^{1x}R_i^{1y}-\sum_i R_i^{2x}R_i^{2y}\right]}{\left(R^{1y}\right)^2+\left(R^{2x}\right)^2-\left(R^{1x}\right)^2-\left(R^{2y}\right)^2}\right\} \tag{25}$$

Under the condition of equation（14）, equations（20）and（21）can be transformed to：

$$\begin{aligned}R(\theta)=\Big\{ & \left[\left(R^{1x}\right)^2+\left(\gamma R^{1y}\right)^2\right]\cos^2\theta+\left[\left(R^{1y}\right)^2+\left(\gamma R^{1x}\right)^2\right]\sin^2\theta \\ & +2\sin\theta\cos\theta\left(1-\gamma^2\right)\left[\sum_i R_i^{1x}R_j^{1y}\right]+\left(R^3\right)^2\Big\}^{\frac{1}{2}}\end{aligned} \tag{26}$$

$$\theta=\frac{1}{2}\tan^{-1}\left\{\frac{2\sum_i R_i^{1x}R_j^{1y}}{\left(R^{1x}\right)^2-\left(R^{1y}\right)^2}\right\} \tag{27}$$

Dongsheng Zhu [22] has ever deduced these equations, but not noticing their essential and limitation. We called these group equations as SRSS3 method. Essentially, SRSS3 method is the simplified form of CQC3 method which does not take into account the dependency relation among modes. If modal correlation coefficients of the structure are small, SRSS3 method will be similar to CQC3 method. If modal correlation coefficients of the structure are large, SRSS3 method will have a rather large error.

APPROXIMATE CALCULATE METHOD FOR MULTI-COMPONENT EARTHQUAKE EXCITATION

For multi-component earthquake excitation, the critical angle θ, which produces the maximum stresses in a particular member or a specified response, may be unique. The above methods are complex and time-consuming for practical engineering. So in the practically engineering, the analyses only combine part of the responses of the structure to single-component earthquake excitation, without considering the input angle. For single-component earthquake excitation, methods for combining modal responses have been developed which account for the correlation between modal responses and obtained accurate results. However, for multi-component earthquake excitation, in spite of many previous studies, the existing methods can be inaccurate.

Square root of sum of squares (SRSS) method

In equation (15), if $\theta=0^o$, we can get Square Root of Sum of Squares (SRSS) method as particular case:

$$R=\left(\left(R^{1x}\right)^2+\left(R^{2y}\right)^2+\left(R^{2z}\right)^2\right)^{1/2} \tag{28}$$

According to equation (14), in order to simplify the analysis we will assume that the minor input spectrum is some fraction of the major input spectrum, fraction is 85%, namely γ=0.85. Substituting this expression to equation (28), we can get the method for multi-component earthquake excitation in seismic design code （GB 50011-2001）. In code section 5.2.3, it is specified that equations for two horizontal directions seismic ground motions. The equations are:

$$S_{EK} = \sqrt{S_x^2 + (0.85 S_y)^2} \qquad (29a)$$

or

$$S_{EK} = \sqrt{S_y^2 + (0.85 S_x)^2} \qquad (29b)$$

where S_{EK} is total response, S_x is the response when the ground motion acts along the X axis of the structure; S_y is the response when the ground motion acts along the Y axis of the structure. It is important to note that the analysis only for the input angle applied at angle of 0° (equation (29a)) or 90° (equation (29b)) in this method. Any reference system or the resulting structure has all members, which is designed to equally resist earthquake motions from all possible directions. However the effect of the input angle is not considered in this method.

Percentage rules

Newmark and Rosenblueth [23] put forward the percentage rules firstly:

$$R = \pm R_1 \pm \alpha R_2 \pm \alpha R_3 \qquad (30a)$$

$$R = \pm \alpha R_1 \pm R_2 \pm \alpha R_3 \qquad (30b)$$

$$R = \pm \alpha R_1 \pm \alpha R_2 \pm R_3 \qquad (30c)$$

One option, in the design codes (UBC97 and Caltrans90) for buildings and bridges, requires that members should be designed for 100 percent of the prescribed seismic forces in one direction plus 30 percent of the prescribed forces in the perpendicular direction. However other codes and organizations (ASCE 4-86 and ATC-32（1996）) stipulate that it should be 40 percent rule rather than 30 percent rule.

ANALYSIS OF VARIOUS CALCULATED METHOD

As described above, SRSS3 method is a simplified form of the CQC3 method. SRSS3 method can be appropriately used to analyze if the modal correlation coefficients of the structure are small. Compared with 0.85-principle and percentage rule, CQC3 method can be applied widely. The critical angle and the associated maximum structural response can be determined by CQC3 method. As we know, a large structure is consisted of great deal of members, which are designed to equally resist earthquake motions from all possible directions. It would be time-consuming for practical engineering if we calculate maximum responses for all components by CQC3 method, and the results for many components would be conservative. Hence only for calculating important response components of critical structure, such as reaction force of piers of large curved bridge, we need to use CQC3 method.

SRSS method and percentage rules have no essential difference. Both of them are simplified ways which reflect effective combination of multi-components from statistic meaning, without considering the effect of the input angle. To be noticed that 0.85-principle and percentage rule have different meanings. Percentage rule is a combination method of the structure responses, and 0.85-principle represents proportional relation of different components of the input motion. Equation (30) and equation (28) should be compared if the two horizontal spectra are assumed same. In code ASCE 4-86, we can conclude this point. This code specified that the conservative results from both the SRSS method and percentage rules should be used to analyze the responses of structure to multi-component earthquake excitation. On the base of equation (28), we can get Equation (29) by adding additional proportion of the components of the input motion.

Many papers have discussed this case, comparing SRSS method and percentage rule. It is not appropriate to compare equations (29) and equation (30). Lopez and Torres [18] indicated some errors in the paper [17]. Furthermore, it should be pointed out that the percentage rules could be refined by including the different intensity of component in the orthogonal direction. Compared with equation (29), the equations of percentage rules should be rewritten as follows:

$$R = \pm R_1 \pm \lambda\alpha R_2 \pm \alpha R_3 \tag{31a}$$

$$R = \pm \lambda\alpha R_1 \pm R_2 \pm \alpha R_3 \tag{31b}$$

$$R = \pm \lambda\alpha R_1 \pm \alpha R_2 \pm R_3 \tag{31c}$$

$$R = \pm \lambda\alpha R_1 \pm \alpha R_2 \pm R_3 \tag{31d}$$

The SRSS method and percentage rules are widely used in practical engineering because of the complexity and time-consuming of CQC3 method. It is important in the practical application in engineering to compare the accuracy of the two methods deliberately. Later, we will show the comparison in the example

The above four methods are all based on spectral mode superposition method. The maximum responses calculated by these simplified methods are approximate. It is necessary to compare them with the exact results calculated by time history analysis. The real earthquake records and the artificial earthquakes computed from standard design spectrum are applied in time history analysis in order to verify these spectra based methods.

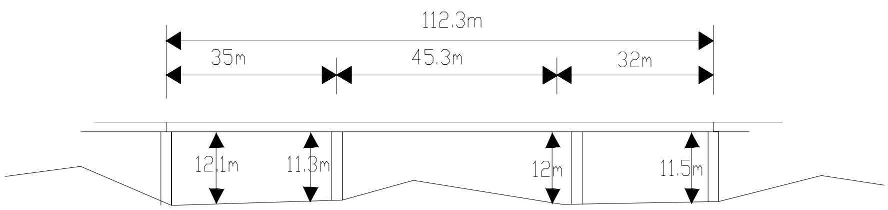


Figure 2 Elevation view of calculated bridge

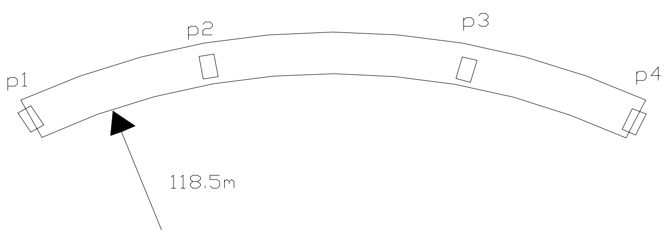


Figure 3 Plan view of calculated bridge

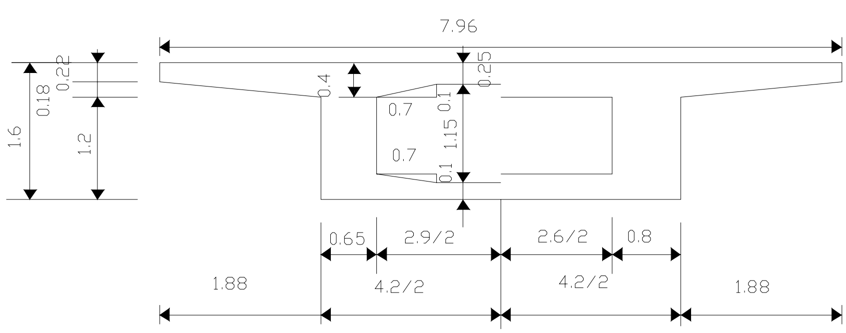


Figure 4 Typical section of superstructure

A numerical example has been conducted in order to examine the results getting from the previously mentioned methods. The calculated bridge is three spans. Figures 2 and 3 are elevation view and plan view of calculated model; figure 4 is a typical section of superstructure. Concrete elastic modulus is 3.5×10^4MP, the mass density is 2500kg/m^3, pier 1 and pier 4 are connected with bearings, the shearing rigidity of bearing is k$=8.8\times10^6$N/m, the nonlinear behavior of isolation bearings is taken into account using horizontal nonlinear spring elements. The analysis model of the example bridge is shown in figure 5.

From equation (8), we need a further analysis based on the analysis of single spectrum when using CQC3 method. If using the sophisticated business programming, we need multi-pass complier. IDARC-BRIDGE [24] is a computational platform for seismic damage assessment of bridges, and we add a new module for spectral analysis into the program. We can combine the analysis results to multi-components for different angles using various methods including CQC3 method, SRSS3 method, SRSS method and percentage rules. It can be concluded from equation (13) that the vertical component is not correlated to the horizontal component, so the effect of the vertical component is not considered in the analysis of numerical model. The responses of structure are illustrated by reaction force of pier 4.

The results of modal analysis and modal correlation coefficients are shown in table 1. It is shown that the coupling between the bearings and curved bridges is significant. The basic frequency is nearly to each other. The modal correlation coefficients are relative large, the largest is 0.973. It can be concluded that the results calculated by SRSS3 method may be not accurate.

Table 1 Periods and mode correlation coefficients

No.	Frequency（Hz）	1	2	3	4	5	6	7	8
1	1.52034	1.00	.717	.825	.057	.043	.011	.007	.005
2	1.59309	.717	1.00	.973	.078	.057	.013	.009	.005
3	1.61740	.825	.973	1.00	.072	.052	.013	.008	.005
4	2.25952	.057	.078	.072	1.00	.719	.042	.022	.012
5	2.40451	.043	.057	.052	.719	1.00	.056	.027	.014
6	3.58757	.011	.013	.013	.042	.056	1.00	.245	.062
7	4.27102	.007	.009	.008	.022	.027	.245	1.00	.187
8	5.27897	.005	.005	.005	.012	.014	.062	.187	1.00

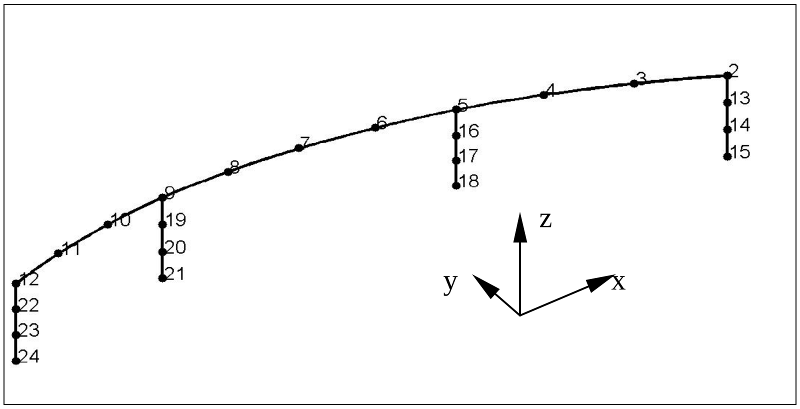
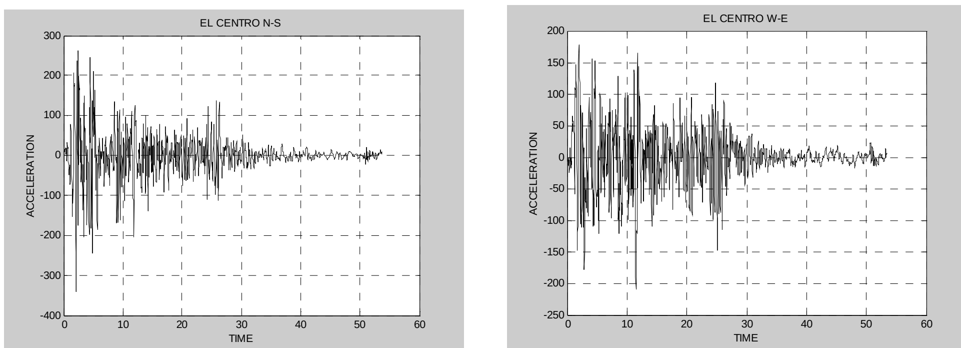


Figure 5 Analysis model

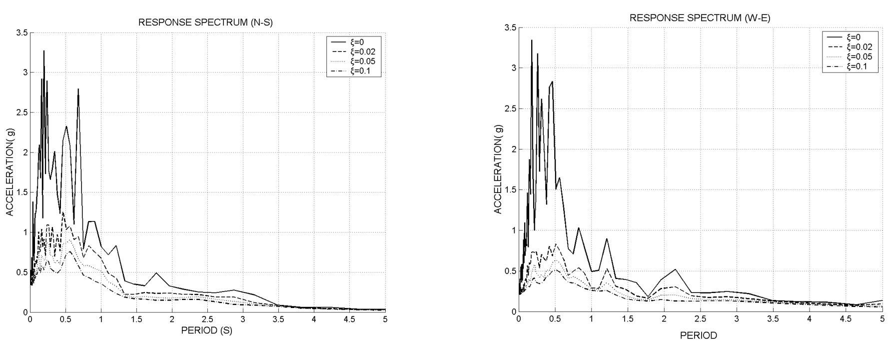
Response of curved bridge for multi-component seismic motion

The simultaneous applications of the two-directional earthquake excitation is considered, which is important to curved bridges. El Centro earthquake accelerogram of May 18, 1940 is used as a dynamic input in this study. The maximum peak acceleration of this record in N-S direction (EL CENTRO S00E) is 0.34g, and in E-W direction (S90W) is 0.21g, where g is the gravitational acceleration. The acceleration records are presented in figure 6. The acceleration response spectra for NS component and EW component are presented in figure 7.



(a) S00E component **(b) S90W component**

Figure 6 Acceleration records of EL CENTRO earthquake



(a) S00E component **(b) S90W component**

Figure 7 Acceleration response spectra for EL CENRO earthquake

Table 2 Maximum reaction force and critical angle of pier 4 using various method

Various methods		V1(N)	V2(N)	V3(N)	M1 (N*m)	M2 (N*m)	M3 (N*m)
SRSS method		6.173e5	6.601e5	9.772e5	2.488e6	1.610e7	3.255e6
Percentage rule（30%）		6.435e5	6.891e5	1.016e6	2.535e6	1.670e7	3.389e6
Percentage rule（40%）		6.644e5	7.071e5	1.035e6	2.553e6	1.699e7	3.505e6
SRSS3	recation force	5.890e5	6.130e5	1.068e6	2.829e6	1.723e7	3.223e6
	Critical angle	54º	24º	78º	78º	78º	54º
CQC3	recation force	6.537e5	6.973e5	1.000e6	2.488e6	1.642e7	3.548e6
	Critical angle	24º	24º	108º	90º	108º	30º
Time history analysis	recation force	6.572e5	6.709e5	9.653e5	2.580e6	1.489e7	3.449e6
	Critical angle	30º	36º	114º	96º	108º	36º

By changing input angle from 0^o to 180^o (increment by 6^o), a series of analysis are investigated for two perpendicular component seismic excitations (S00E component and S90W component), using CQC3 method, SRSS3 method, percentage rules and SRSS method. At the same time, the time history analysis of bridge is carried out for different angle. As the assumption that two components are uncorrelated, we combine the maximum responses for two components using SRSS method. The results are presented in table 2. The curves of reaction force with respect to input angle are presented in figure 8. We can obtain some rules from the results of the study.

1. The effect of different input angles cannot be neglected for two-component earthquake excitation. In this paper, showed by the numerical model, the variation amplitude of maximum response with respect to different input angles, are above 30%, the largest is 45%.

2. The results calculated by CQC3 method and time history analysis are similar. It indicates that the CQC3 method is accurate relatively. It seems that more attention should be paid to verify the CQC3 method by practical time history analysis.

3. Results calculated by SRSS method actually are the larger one which is calculated by CQC3 method for input on 0° or 90°. The accuracy of this method is determined by the irregularity of the structure and the critical angle corresponding to the maximum response, since the influence of the different input angles is not taken into account in this method. In this example, the maximum response nearly appears at angle 0° or 90°, so the error is small. This method would have a relative large error, and the error would be not conservative, if the maximum response critical angle appears far from 0° or 90°.

4. When percentage rule is 30%, most responses are conservative, and exceptional case seems few. If percentage rule is 40%, all reaction forces are larger than the maximum responses of time history analysis. From the analysis of the example-curved bridge, the percentage rule is better than SRSS method.

5. SRSS3 method is able to calculate the variation of structural responses caused by different input angles. The modal correlation coefficients in this example curved bridge are relative large, so the error is also quite large in this case. It seems necessary that an application range of SRSS3 method should be specified to avoid probable large error.

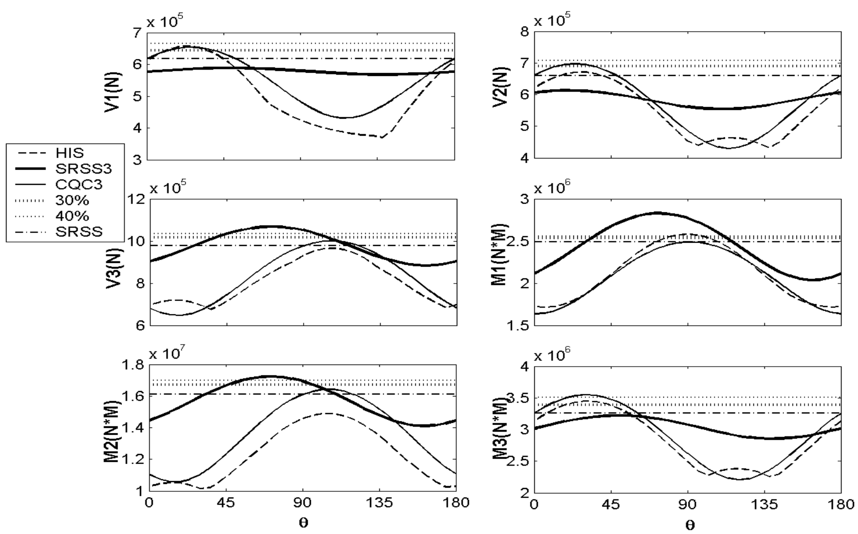
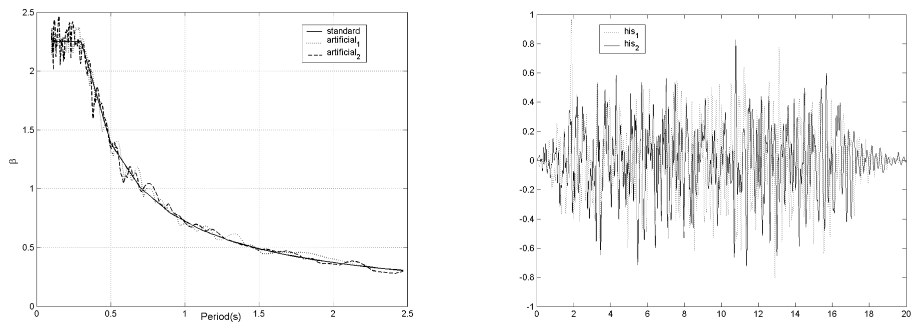


Figure 8 Reaction forces of pier 4 using various methods
(Time history analysis, CQC3 method, SRSS, percentage rules)

Response of curved bridge for standard spectrum and artificial earthquakes

The standard spectra are generally used to carry out seismic response analysis in seismic design code. The analysis model is described in figure 5. For standard design spectrum excitation, principal direction ground motion parameters should be adopted as specified in Chinese seismic design code for highway engineering (JTJ 004－89) [25]. Assume the design basic intensity is 8 which is equivalent to MM intensity scale and the bridge is located at site of second-class according to the site classification in Chinese seismic design code. The design horizontal earthquake coefficient is $K_h = 0.2$ and the corresponding design spectrum is shown in figure 9-a. Another component perpendicular to the principal direction is adopted according to prescribed proportion in seismic design code. An artificial earthquake wave sample computed from standard design spectrum is applied for time history analysis, which is presented in figure 9-b, where γ is ratio of one component to the other. In synthesizing artificial earthquake waves the cross correlation function of two direction artificial earthquake waves is controlled lower than 0.1.



(a) Standard spectrum and spectrum of artificial earthquakes **(b) artificial earthquakes**

Figure 9 Standard spectrum and artificial earthquakes

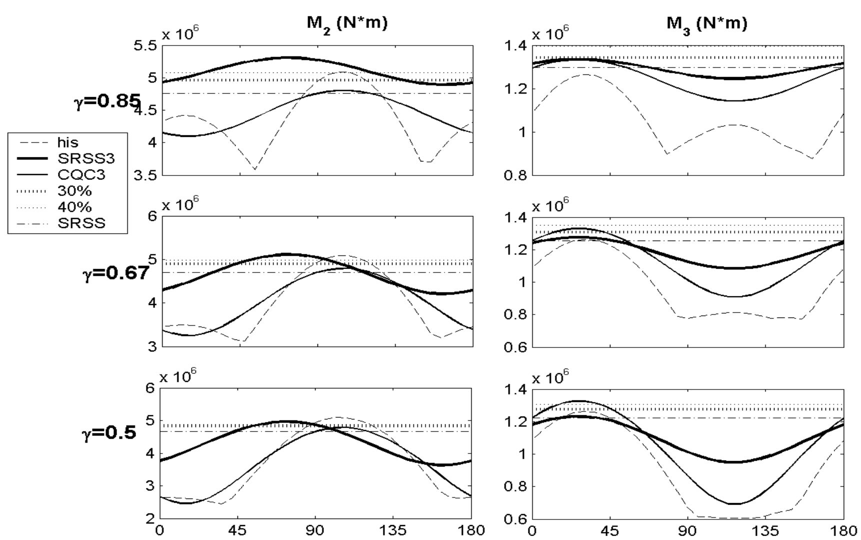


Figure 10 Reaction forces of pier 4 using various methods for standard spectrum (Time history analysis, CQC3 method, SRSS, percentage rules)

The results computed by various methods are shown in figure 10. From the results, it can be concluded that:

1. When γ is set for 0.85, 0.67 and 0.5, the critical angle of response is identical at different ratio coefficient. This is consistent with the equation (16) which indicates the independency of θ.

2. The artificial earthquake waves are computed from identical design spectrum, but the effect of phase is significant. Especially when the amplitudes of two-component are close to each other, the difference between results of time history analysis and CQC3 method is large at some input angle. Generally the critical angle and maximum response is accurate, so the CQC3 method is a feasible approach in practical engineering design.

3. The reason of the difference between the results calculated by SRSS3 method and CQC3 method is the same as mentioned above.

4. The SRSS method does not take into account the influence of the input angle, so the response of structure sometimes is unsafe. However the maximum responses appear nearly at angle 0° or 90° in this example, the results of SRSS method and CQC3 method are relatively close to each other.

5. When percentage rule is 30%, most responses are conservative, and exception is few. If percentage rule is 40%, all reaction forces are larger than the maximum responses calculated from time history analysis. From the analysis of example-curved bridge, the percentage rules are preferred to SRSS method.

CONCLUSIONS AND SUGGESTIONS

In this article, the methods of multi-component seismic analysis for curved bridges are systemically analyzed and compared. From the extensive study and comparison by CQC3 method and SRSS3 method, SRSS3 method is well illustrated, and its applicable range and limitation are also pointed out. Meanwhile the theory and parameter analyses of simplified methods are conducted in this paper. The seismic responses of a curved bridge are calculated in various ways based on real response spectrum and standard design spectrum. To verify these methods, the real earthquake records and the artificial earthquake waves computed from standard design spectrum are applied for time history analysis. The main results and conclusions of the study may be summarized as follows.

a) The effect of input angle for multi-component seismic excitation to curved bridges is relatively large. It may be not reasonable for the practical engineering design if this factor is neglected.

b) Compared with time history analysis, the CQC3 method usually is sufficient accurate. However compared with the SRSS method and percentage rules, it is more complex. For the important structure, it is necessary to employ CQC3 method to carry out analysis.

c) SRSS3 method is the simplified form of CQC3 method. SRSS3 method would have a rather large error if the natural periods of the structure are close to each other, namely modal correlation coefficients of structure are large.

d) The SRSS method is convenient to the analysis of structure; perhaps due to its simplification many seismic codes adopt it as normal combination method for multiple mode seismic responses. The accuracy of this method depends upon the irregularity of the structure and the critical angle corresponding to the maximum response, since the influence of the different input angles is not taken into account in this method.

e) The results of percentage rules are usually conservative, and in most cases are reasonable. From these conclusions, several suggestions can be drawn as follows for fitting the need of code and seismic design of curved bridges or other irregular structures.

1. Current Chinese seismic code specifies that using 85% principle is too simple and the effect of different input angles is not taken into account. It becomes necessary to do further study and modification. It is suggested to use various analytical methods to fit the practical need of seismic design for different kind of structures.

2. In seismic design of important curved bridges, it is prefer CQC3 method and time history analysis to calculated critical angles and maximum responses of structures.

3. In the seismic design code of highway engineering, appropriate mode superposition method should be specified. It is suggested to use the conservative results from percentage rules and SRSS method in seismic design of curved bridges in consideration of the influence to multi-component seismic excitations.

ACKNOWLEDGEMENT

This research is funded by Beijing Municipal Educational Commission and Beijing Laboratory of Earthquake Engineering and Structural Retrofit, Beijing University of Technology, China. These financial supports are gratefully acknowledged.

REFERENCES

1. Tseng W. S, Penzien J. "Seismic analysis of long multiple-span highway bridges." Earthquake Engineering and Structural Dynamics, 1975, 4: 3-24.
2. Tseng W. S, Penzien J. "Seismic response of long multiple-span highway bridges." Earthquake Engineering and Structural Dynamics, 1975, 4: 25-48.
3. David Williams, William Godden. "Seismic response of long curved bridge structures: experimental model studies." Earthquake Engineering and Structural Dynamics, 1979, 7:107-128.
4. Kawashima K, Penzien J. "Theoretical and experimental dynamic behavior of a curved model bridge structure." Earthquake Engineering and Structural Dynamics, 1979, 7:129-145.
5. Li Guohao, Shi Dong. "Finite analysis of seismic response of curved girder bridges." Journal of Tongji University, 1984, 1:1-21.
6. Desroches R, Fenves G. L. "Evaluation of recorded earthquake response of a curved highway Bridge." Earthquake Spectra, 1997, 3(3):363-386.
7. Zureick A, Naqib R. "Horizontally curved steel I-girders: state-of-the-art analysis methods." Journal of Bridge Engineering, 1999, 4(1): 38-47.
8. Heinere Howard. "Girder flange and cross-frame members earthquake induced stress: comparing straight and horizontally curved bridge elements." Research Experience for Undergraduates, Univ. Alabama at Birmingham. 1999.
9. Maneetes H. "The effects of cross-frame geometry on the dynamic response of curved steel I-grider bridges during construction." Thesis Submitted for Master of Science, the Pennsylvania State University, 2001.
10. Penzien J, Watabe M. "Characteristics of 3-dimensional earthquake ground motion." Earthquake Engineering and Structural Dynamics, 1975, 3: 365-373.
11. Wilson E. L, Button M. R. "Three-dimensional dynamic analysis for multi-component earthquake spectra." Earthquake Engineering and Structural Dynamics, 1982, 10: 471-476.
12. Smeby W, Der Kiurghian. "Modal combination rules for multi-component earthquake excitation." Earthquake Engineering and Structural Dynamics, 1985, 13: 1-12.
13. Wilson E. L, Suharwardy I, Habibullah A. "A clarification of the orthogonal effects in a three-dimensional seismic analysis." Earthquake Spectra, 1995, 11: 659-666.

14. Lopez O. A, Torres R. “Discussion of ‘A clarification of the orthogonal effects in a three-dimensional seismic analysis’ by Wilson E. L, Suharwardy I, Habibullah A.” Earthquake Spectra, 1996, 12:357-365.
15. Reed J. W, Kennedy R. P. “Discussion of ‘A clarification of the orthogonal effects in a three-dimensional seismic analysis’ by Wilson E. L, Suharwardy I, Habibullah A.” Earthquake Spectra, 1996, 12: 353-356.
16. Lopez O. A, Torres R. “The critical angle of seismic incidence and the maximum structural response.” Earthquake Engineering and Structural Dynamics, John Wiley& Sons, 1997, 26:881-894.
17. Menun C, Kiureghian A. D. “A replacement for the 30%, 40% and SRSS rules for multicomponent seismic analysis.” Earthquake Spectra, 1998, 14: 163-163.
18. Hernandez J. J, Lopez O, A. “Discussion of ‘A replacement for the 30%, 40% and SRSS rules for multicomponent seismic analysis’ by Charles Menun and Armen Der Kiureghian.” Earthquake Spectra, 1998, 14:713-715.
19. ASCE-4-86. “Seismic analysis of safety-related nuclear structures and commentary on standard for seismic analysis of safety related nuclear structures.” American Society of Civil Engineers, Sept. 1986.
20. Code for seismic design of buildings (GBJ111-87). Beijing: China Building Press, 1989.
21. Wilson E. L, Der Kiureghian S, Bayo E. P. “A replacement for the SRSS method in seismic analysis.” Earthquake Engineering and Structural Dynamics, 1981, 9:187-194.
22. Dongsheng Zhu, Lusong Yu, Shizhong Liu. “The Study of earthquake input principal direction for irregular bridges.” Journal of Lanzhou Railway University, 2000, 19(6): 37-40.
23. Rosenblueth E, Contreras H. “Approximate design for multicomponent earthquakes.” ASCE J. Eng. Mech. Div, 1977, 103(5):881-893.
24. Reinhorn A. M, Simenov V. “IDARC-BRIDGE: A computational platform for seismic damage assessment of bridge structures.” MCEER, Tech. Report MCEER-98-0011, 1998.
25. The code for seismic design of highway engineering (JTJ 004－89). Beijing:Renmin Jiaotong Press, 1990.