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Seismic analysis of bridges based on stress-dependent damping

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Abstract. Damping value has considerable influence on the dynamic and seismic behaviors of bridges. However, currently the constant damping ratios that are prescribed by most bridge seismic design codes can't truly represent the complicated damping character of actual structures. In this paper, a cyclic loading experiment was conducted to study the effect of stress amplitude on material damping of concrete to present an analyzing model of the material damping of concrete. Furthermore, based on the fundamental damping of structure measured under ambient vibration, combined with the presented stress-dependent material damping concrete, the seismic response of a bridge pier was calculated. Comparison between the calculated and experiment results verified the validity of the presented damping model. Finally, a modified design and analysis method for bridge was proposed based on stress-dependent damping theory, and a continuous rigid frame bridge was selected as the example to calculate the actual damping values and the dynamic response of the bridge under different earthquake intensities. The calculation results indicated that using the constant damping given by the Chinese seismic design code of bridges would overestimate the energy dissipation capacity of the bridge.

Keywords: cyclic loading experiment; stress-dependent damping; seismic design of bridge; response spectrum

1. Introduction

Bridges play an important role in daily transportation and post-disaster relief work (Kawashima *et al.* 2009). The seismic performance of bridges should be analyzed accurately, in order to ensure the safety of bridges under earthquake action. Damping characterizes structure energy dissipation capacity in the process of vibration. As an important factor in calculating the dynamic response of bridges, the value of damping directly affects the precision of bridge dynamic response analysis (Clough and Penzien 1977). At present, since viscous damping model is most widely accepted in the description of dynamic behavior of structures, and for simplicity in engineering calculation and analysis, the viscous damping coefficients are generally defined as constant (Liu *et al.* 2005). Most of the bridge seismic design specifications also adopt a constant damping ratio value which generally uses 5% for concrete structures, and relevant modified methods were proposed for other damping ratio values (MOT 2008, CEN 2003, Caltrans 2010). In general, it is difficult to give specific damping ratios for different structures in the seismic design specifications (Hart and Vasndevan 1975, Wen and Wang 2005).

A series of experimental studies and theoretical analysis have been conducted on the damping ratio of bridges. Farrar *et al.* (1999) systematically introduced the excitation methods for determining the modal characteristics (resonant frequencies, mode shapes and modal damping ratios) of bridge and the features of different methods. Okauchi *et al.* (1986) tested the damping property of a suspension bridge by using a 20 tons vibration exciter, the damping ratio of the first mode was 0.53%. Some researchers tested 23 steel and composite bridges (span range is 17 m to 213 m) by using free decay method, the results show that the damping ratio has obvious correlation with amplitude, the damping ratio increases with the increasing of amplitude (Eyre and Tilly 1977, Tilly 1977). The value of the damping ratios were presented based on the measured data, for reinforced concrete bridge is 2%~10%, steel bridge between 2%~6%, and composite girder bridge is 5%~10%. Green (1977) collected the test damping ratio data of the bridges in Ontario, Canada from 1956 to 1971. The data show that the damping ratio of the bridges with less than 75m span varies between 0.15%~0.64%, and the bridges with more than 125m span varies between 0.64%~0.95%. Billing (1982; 1984) tested 27 steel, timber and concrete bridges in Ontario, Canada, by using moving vehicle testing. The damping ratio ranges of the different bridges were proposed, 0.4%~0.7% for steel bridge, and 0.8%~3.8% for concrete bridge. In recent years, González *et al.* (2012) proposed a rapid identification method of damping in a bridge using a moving instrumented vehicle. Therefore, the

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damping properties of bridges are significantly influenced by complicated factors such as materials, bridge types, test method, should not be simply expressed as a constant damping ratio.

A constant damping ratio cannot precisely describe the energy dissipation capacity of structures under earthquake. By evaluating damping experimentally, some studies showed that damping depends upon many factors that cause the non-linear property, such as displacement ductility, stress, temperature, etc. Lu *et al.* (2001) observed that effective damping is influenced by the displacement ductility of RC frames, and deduced an effective damping ratio relationship based on their dynamic tests. Wang and Li (2013) proposed the non-linear material damping model of FRP confined column, the damping property was tested considering different stress amplitudes and initial damages at the same time. Audenino *et al.* (2003) established the theoretical relation between temperature and internal damping in metals through thermographic analysis and specific damping measurement.

Lazan (1968) conducted a great deal of tests on damping of different materials, showing that the damping is affected by stress amplitude. He established the relation between damping and stress of material. The relationship between energy dissipation per unit volume and stress amplitude can be expressed as follow

$$\Delta U(\sigma) = J\sigma^n \tag{1}$$

where, $\Delta U(\sigma)$ is dissipation energy per unit volume of material, σ is stress amplitude, J, n are the coefficient of material and stress level, respectively.

The damping can be defined as the loss factor described by the ratio of dissipation energy to total strain energy, it can be expressed

$$\eta = \frac{1}{2\pi} \cdot \frac{\Delta U}{U} \tag{2}$$

where U is total strain energy and ΔU is the dissipation energy of damping.

The loss factor proposed by Lazan, is the rudiment of stress-dependent damping. The stress-dependent damping theory is based on material damping, which reflects the essence of energy dissipation of material and has physical meaning. Following this idea, Kume (1982) also proposed a similar method and presented a damping-stress diagram for a cantilever beam, assuming that the stress amplitude developed in the beam was applied to evaluate the loss factor for every natural frequency. Gounaris *et al.* (1999, 2007) first proposed a finite element iteration method for calculating the loss factors of a steel cantilever beam based on the damping-stress function proposed by Lazan. Wen and Wang (2007, 2008) studied the stress-dependent damping of concrete and reinforced concrete members, and gave the relevant expression of stress-dependent loss factor of the members. Wang and Li (2008) analyzed a reinforced concrete frame structure by using stress-dependent damping theory. As mentioned above, the stress-dependent damping property of structural component has attracted much attention, but the material damping with stress-dependent property has not been sufficiently studied. In addition, these damping models for structural component do not get wide application because of their complex parameter identification and computation.

Fig. 1 Loading equipment

Based on the experimental and theoretical studies discussed above. In this paper, a cyclic loading experiment was proposed to test the effect of stress amplitude on the material damping of concrete, and a formulation of the relationship between the loss factor and stress amplitude of concrete was obtained. Then, the stress-dependent damping of concrete material was introduced into the dynamic analysis of structural component based on some assumptions about the constitution of structural damping. And a bridge pier was calculated, validating that the material damping model is feasible for dynamic analysis of structural component. Finally, the stress-dependent damping theory was introduced to improve the response-spectrum method for the seismic design of bridges. A continuous rigid frame bridge was selected as the example to demonstrate the difference of the dynamic responses under constant and varied damping ratios.

2. Stress-dependent damping of concrete under cyclic loading

An experiment was conducted to evaluate the effect of stress amplitude on the energy dissipation characteristics of concrete under axial cyclic loading. The specimen size in this experiment is 100 mm×100 mm×300 mm, and the concrete strength grade is C50.

The electro-hydraulic servo machine was used as the loading equipment with the capacity of ±500 kN and maximum loading frequency of 100 Hz, as shown in Fig. 1.

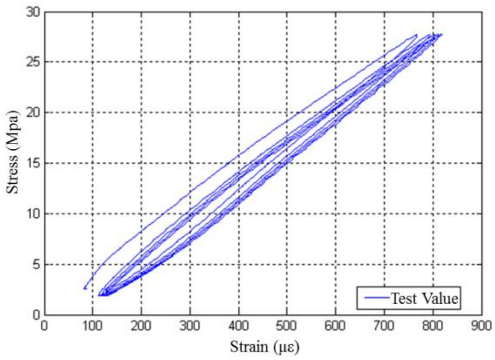
Resistance strain gages were pasted in the middle of each specimen surface, as shown in Fig. 2. In order to achieve synchronous output of loading force and strain values, dynamic strain gauges were accessed to the MTS servo apparatus operating platform.

Table 1 shows the details of loading conditions. σ means the average stress, $\Delta\sigma$ denotes the stress amplitude and ω is the loading frequency. Sine wave was selected as loading

Fig. 2 Strain test equipment

Table 1 Loading conditions

Load conditions	σ (MPa)	σ (MPa)	ω (Hz)
A-25	15	25	1
A-20	15	20	1
A-15	15	15	1
A-10	15	10	1
A-5	15	5	1



(a) The first five hysteresis loops

Fig. 3 Hysteresis loops under A-25 condition

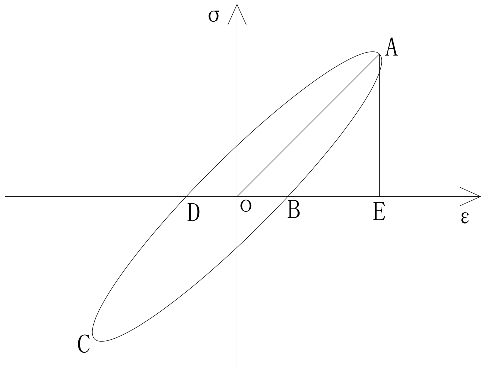
wave, and the cyclic number of each condition is 30.

Fig. 3 shows the first five hysteresis loops and the tenth hysteresis loop under A-25 condition. The test results indicate that the shape of hysteresis curve remains stable during the loading process, as shown in Table 2, the area of hysteresis loop stands for the energy dissipation under sine wave load of each cycle. Statistical analysis of the area of all the 30 hysteresis loops under A-25 condition shows that the mean value is 4774 and the standard deviation is 42. Under the other load conditions, the standard deviations of the areas are all less than 80.

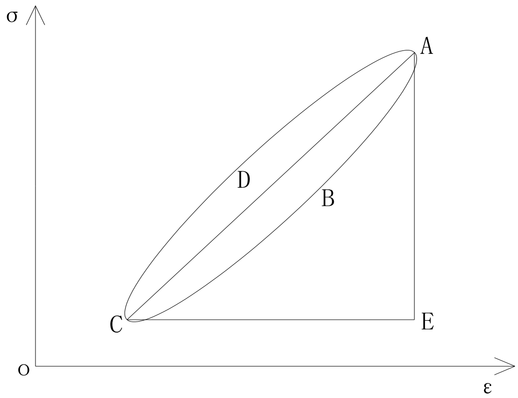
ψ is defined as the ratio of dissipation energy to total strain energy for viscoelastic material, as shown in Fig. 4(a). The maximum storage energy area of the hysteresis loop in the area of S_{CAE} shown in Fig. 4(b), is four times of the area of general viscoelastic material S_{OAE}, as shown in

Table 2 Energy dissipation of each cycle under A-25 load condition

Number of hysteresis loop	Energy dissipation (kN.$\mu\varepsilon$)	Number of hysteresis loop	Energy dissipation (kN.$\mu\varepsilon$)	Number of hysteresis loop	Energy dissipation (kN.$\mu\varepsilon$)
1	4854	11	4763	21	4765
2	4699	12	4765	22	4763
3	4738	13	4768	23	4761
4	4886	14	4778	24	4774
5	4823	15	4680	25	4774
6	4780	16	4690	26	4780
7	4724	17	4850	27	4773
8	4790	18	4775	28	4776
9	4775	19	4778	29	4781
10	4790	20	4779	30	4777



(a) Hysteresis loop of viscoelastic material



(b) Hysteresis loop in this paper

Fig. 4 Diagram of hysteresis loop

Fig. 4(a). So the loss factor should be corrected as Eq. (3).

$$\eta = \frac{\psi}{2\pi} = \frac{4\Delta U}{2\pi U} = \frac{4S_{ABCD}}{S_{CAE}} \tag{3}$$

Based on the Eq. (3), the loss factor is calculated in Table 3. The unit of energy dissipation per cyclic is mJ.

From the Table 3, it can be concluded that the strain decreases with the decreasing of loading force, and the decay value is linearly related to the loading force. The loading force has slight influence on the secant modulus of concrete, which indicates that the specimen is still in elastic stage. It also can be found that the dissipate energy and

Table 3 Loss factors under amplitude-related conditions with sine wave loading

Load Conditions	$\Delta\varepsilon$ ($\mu\varepsilon$)	Secant modulus (104MPa)	ΔU (mJ)	U (mJ)	η
A-25	716	3.49	1432.2	25762.5	0.035
A-20	569	3.51	532.2	16230	0.021
A-15	430	3.49	246.3	9000	0.017
A-10	270	3.70	93	4050	0.015
A-5	153	3.27	14.1	1012.5	0.009

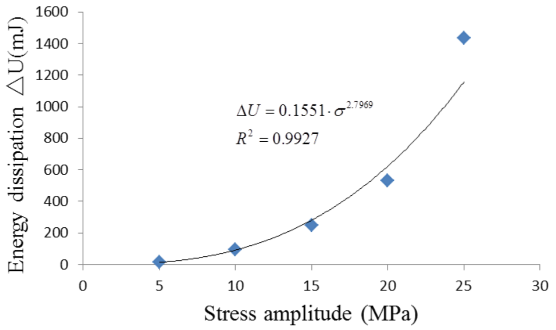


Fig. 5 Relationship of stress amplitude and energy dissipation

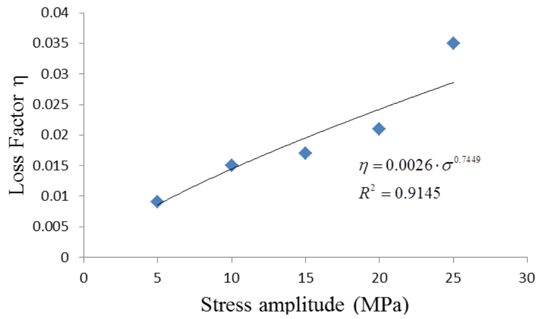


Fig. 6 Relationship of stress amplitude and loss factors

storage energy decrease with the decreasing of stress amplitude, and the decreasing trend of the dissipate energy is lower than that of the storage energy.

The formulas of the relationship between the energy dissipation, loss factor and stress amplitude were fitted by using power function, as shown in Fig. 5 and Fig. 6.

$$\Delta U = 0.1551 \times \sigma^{2.7969} \qquad R^2 = 0.9927 \tag{4}$$

$$\eta = 0.0026 \times \sigma^{0.7449} \qquad R^2 = 0.9145 \tag{5}$$

The loss factor per unit volume can be employed to describe the energy dissipation capacity of material. Here, the loss factor per unit volume of concrete is the energy dissipation ΔU divide the volume of the specimen (0.003 m^3).

3. Stress-dependent damping used in dynamic analysis of structural component

Even though various damping models have been proposed for seismic design of structures, these models has not got wide applications. At present, in most seismic design specifications, the constant damping ratio is still used to estimate the seismic response of structures. At least three root causes are responsible:

1) In order to describe the energy dissipation capacity more accurately, the proposed damping models always introduce more parameters which make the models more complicate. Meanwhile, the relevant parameters are difficult to identify.

2) The complexity of the damping models makes the calculation difficulty and learning cost for engineers increasing largely.

3) For the actual structures, the energy dissipation can be caused by various factors, but most of the proposed damping models do not have specific physical meaning.

Although the imperfection of constant damping ratio is widely acknowledged, the seismic design method for bridge has been barely modified for the foregoing reasons. Therefore, it is significant to develop a method to clearly describe the damping characteristic under earthquake, which is simple enough to express concisely, and yet can avoid complex parameter identification and computation. In this paper, to satisfy the above conditions, two assumptions are made as follow:

1) As Chopra (1995) mentioned that it would overestimate the viscous damping, if all the plastic energy dissipation attribute to damping energy dissipation. Therefore, the material damping of concrete in elastic stage is employed to calculate the dynamic response of bridge under earthquake, which benefits the safety of structures.

2) In general, the structure damping has complex components (Rainieri *et al.* 2010). In this paper, the structure damping is divided into two parts: internal damping, which is contributed by material, external damping, which is contributed by structural connections, soil-structure interfaces, etc. Under ambient excitation, the external damping plays a major role in the energy dissipation, and the internal damping will participate in the energy dissipation at high stress level. Therefore, this paper defines that the external damping obtained under ambient vibration as the fundamental damping of the structure.

Based on the assumptions, the material damping model of concrete established above can be applied in dynamic analysis of structural component.

Besides, the proposed stress-dependent damping will be converted into equivalent viscous damping ratio, which is used for seismic computation and design of structure. Based on the Eq. (3), the loss factor could be obtained from U and ΔU, in a single degree of freedom system under harmonic load, which can be expressed as

$$U = \frac{1}{2} k X^2 \tag{6}$$

$$\Delta U = \oint C_e \dot{x} dx = \int_0^{\frac{2\pi}{\theta}} C_e X^2 \theta^2 \cos^2 \theta t dt = \pi C_e \theta X^2 \tag{7}$$

where, X is the amplitude of response, θ is the loading frequency, C_e is the critical damping coefficient.

Substituting Eq. (6) and (7) into Eq. (3), we can obtain

$$C_e = \frac{\eta k}{\theta} \tag{8}$$

For a viscous damping system, the critical damping coefficient can be expressed as

$$C_e = 2\xi m\omega \tag{9}$$

where, ξ is the viscous damping ratio, m is the mass, ω is the natural frequency of the system.

Substituting Eq. (9) into Eq. (8), we can obtain the relationship between the viscous damping ratio and loss factor as follow

$$\eta = 2\xi\frac{\theta}{\omega} \tag{10}$$

In this paper, the proposed stress-dependent damping will be converted into an equivalent viscous damping ratio, and used for seismic analysis and design of structures. The test data of a column in the reference (Ai *et al.* 2008) are selected to verify the usage of stress-dependent damping in dynamic analysis of structural component. The Midas Civil software is employed to establish a finite-element model of the specimen. The constitutive model of concrete is the Takeda three line hysteretic model (Takeda *et al.* 1970). The Takeda three line hysteretic model considers stiffness degradation in the process of unloading, so it is widely used in the elastoplastic dynamic analysis of reinforced concrete structure. The detailed information of the model is shown in Fig. 7.

Take the A10 column from the reference (Ai *et al.* 2008), for instance, the finite-element model of the A10 column is shown in Fig. 8.The calculated natural frequency of the A10 column is 2.4 Hz, the measured value is 2.56 Hz and relative error is 5.9%, so the validity of the finite-element model is verified.

The computed damping ratio is based on the structural damping ratio, combined with the stress-dependent damping ratio caused by stress rising. In the reference (Ai *et al.* 2008), the damping ratio of the column after a minor earthquake was measured, but the initial damping ratio was not measured. Based on the measured data, the fundamental damping ratio is set as 2.5% in this paper. At first, the initial damping ratio is supposed to be 5%, the time-history curve of every element is calculated by the FEM method under the El Centro seismic wave. The stress time-history curve of the lateral element at the bottom of the column is shown in Fig. 9. The positive direction is compressive stress.

The stress amplitude of each element is calculated according to the maximum stress amplitude during the overall process, then substituting the maximum stress into Eq. (5). The stress dependent damping of the concrete column is calculated to be 2.96%, which is slightly larger than the measured value that is 2.8%.

Fig. 10 shows the comparison of the top displacement of the column between measured results and calculated results which are obtained by using the stress-dependent damping ratio and constant damping ratio (5%). Under minor earthquake, the gap of dynamic response of the column between the results calculated by stress-dependent damping ratio and the measured result is 2.2%, but the gap between the results calculated by constant damping ratio and measured result is 10.8%. Therefore, calculation based on the stress-dependent damping ratio achieves much higher

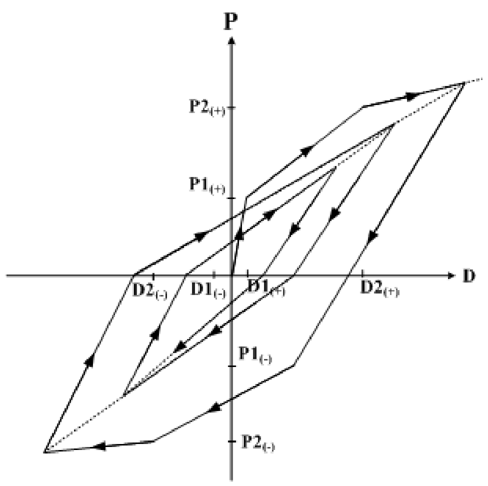


Fig. 7 The Takeda three line hysteretic model

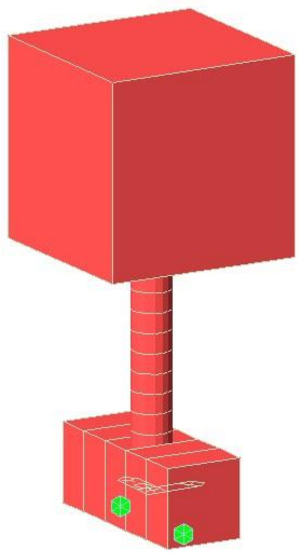


Fig. 8 The finite model of A10 column

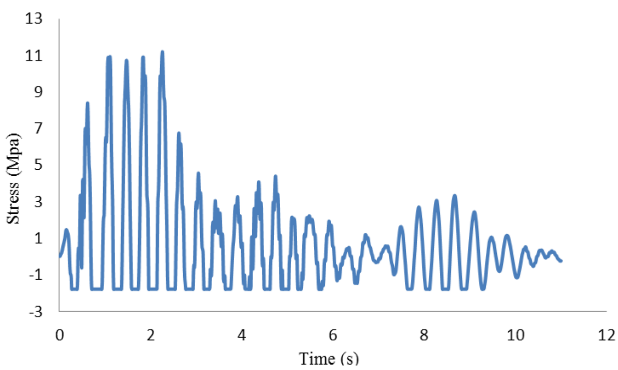


Fig. 9 Stress time travel curve of the lateral units at the bottom of the column

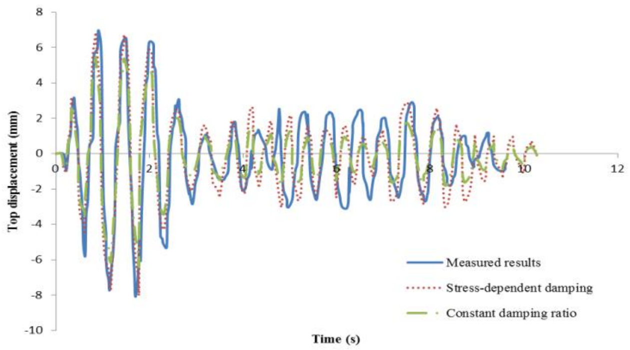


Fig. 10 Comparison of measured results and calculated results

accuracy. For mediate-earthquake and severe earthquake, the stress-dependent damping ratios are 4.6% and 6.1%, which are far more than the damping ratios of the measured value after impacting, which are 3.5% and 3.7%, respectively.

With the increase of seismic intensity, the damping ratio of the column increases. The measured damping ratios are obtained by using free decay method after loading completes, and the growth trend of damping ratios is not as significant as the increasing of seismic intensity. However, by using the stress-dependent damping model, the damping ratio shows a significantly increment with the increasing of seismic intensity. During a strong earthquake, the internal friction in and among material increases with the development of plasticity and internal damage. In macroscopic view, the energy dissipation is enhanced. After earthquake, the amplitude of vibration decreases significantly, the influence of plasticity and damage on the damping is reduced accordingly and the damping energy dissipation effect gradually abates and disappears. Therefore, the measured damping ratio of the column is less than the one calculated by stress-dependent theory. In dynamic analysis of structures, the stress-dependent damping can better reflect the actual performance of structures. Moreover, it also confirms the assumptions mentioned above, that the material damping model is feasible for dynamic analysis of structural component.

4. Stress-dependent damping in the bridge seismic design

4.1 Modified seismic design response spectrum based on the stress-dependent damping theory

At present, the response spectrum method is the most widely used in seismic design of bridges. The standard response spectrum specified in seismic design code of different countries is the typical average response spectrum curve obtained by analyzing and counting massive seismic response spectrum curves and it is the basis of design. In addition, the standard response spectrum, which is then used for design and calculation, should be modified based on the specific condition of structures. There are many factors that influence the design response spectrum curve, including site location, site condition, structural natural frequency, damping ratio and so on. For the regulation of damping ratio value, the provisions specified in seismic design code of different countries are different.

In China's Guidelines for Seismic Design of Highway Bridge (JTG/T B02-01-2008) (MOT 2008), it stipulates that, excepting some special situation, the structural damping ratio of reinforced concrete bridges ξ should be 5%; if the damping ratio is not 5%, the correction coefficient of damping should be modified by relevant formulas.

In Eurocode-8: Design of Structures for Earthquake Resistance, Part 2: Bridges (CEN 2003), it stipulates that, when response spectrum analysis is used, the following values of equivalent viscous damping ratio ξ may be assumed based on the material of the members where the larger part of the deformation energy is dissipated during the seismic response. The damping ratio of 4 types of bridge are provided with welded steel 0.02, bolted steel 0.04, reinforced concrete 0.05 and prestressed concrete 0.02.

In Caltrans Seismic Design Criteria (Caltrans 2010), it stipulates that, for structural applications, seismic demand is represented using an elastic 5% damped response spectrum. The following characteristics are typically good indicators that higher damping may be anticipated: total length less than 300 feet (90 m), three spans or less, abutments designed for sustained soil mobilization; normal or slight (less than 20 degrees) and continuous superstructure without hinges or expansion joints.

Generally speaking, in these codes of different countries, the structural energy dissipation capacity is mainly considered using the response spectrum modified by damping ratio. The different damping ratios have obvious influences on the response spectrum curve, including the height of platform, the decay rate of descending part. The revised methods adopted in different codes are slightly different. From these codes it can be seen that the most commonly proposed damping ratio is 0.05 for reinforced concrete bridges, or a specific value can be given according to the structural form and material of bridges.

Due to the simplicity of the viscous damping theory in mathematics, for a long time, the damping ratio is always a main parameter to evaluate the damping of structure. The damping ratio values given in the codes are obtained from the statistics of a large number of measured data which are based on viscous damping theory. However, a lot of research and measured data show that the damping values will change significantly with the increasing of stress level. Therefore, the energy dissipation capacity of structure cannot be precisely described by a constant damping under the earthquake action. In recent years, in order to improve the traditional viscous damping model, various precise damping models are proposed and applied in the dynamic analysis of structures including stress-dependent damping model, strain-dependent damping model and exponential damping model (Pan and Wang 2015), however, these models have not widely used in the seismic design of structures. This is because the parameters of these models are not explicit, and the computational processes are quite complicated. Under these situations, this paper proposes a

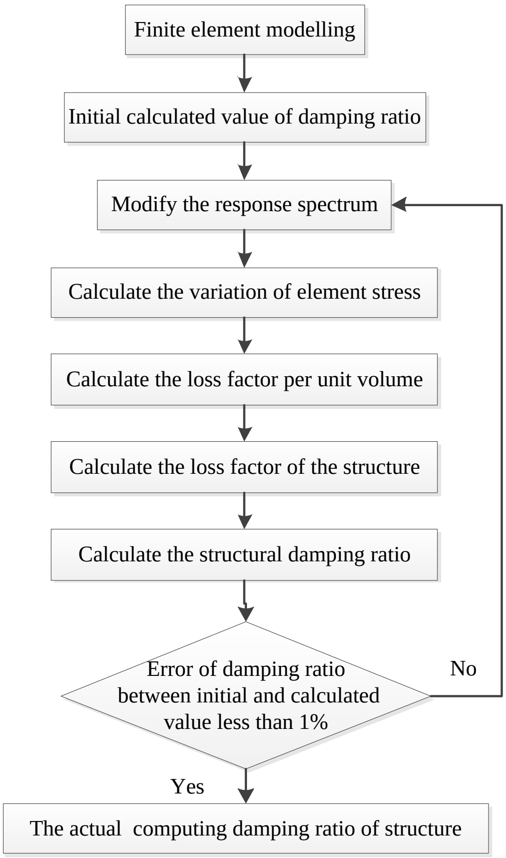


Fig. 11 Calculation flow of structural dynamic analysis with stress-dependent damping ratio

modified seismic design response spectrum based on the stress-dependent damping theory.

The calculation procedure of stress-dependent damping ratio is as follow. Firstly, assume the initial damping ratio of bridge structure is 5%, and calculate the stress amplitude of each element according to the response spectrum. Secondly, the corresponding loss factor per unit volume can be calculated by the stress amplitude of each element, the loss factor of the whole structure can be obtained by combining the volume of each unit, and then the stress-dependent damping ratio can be calculated. Finally, substitute the stress-dependent damping ratio for the initial damping ratio. After repeated iteration, the accuracy is considered to meet the requirements when the error is less than 1%, and the obtained damping ratio is the stress-dependent damping ratio. The specific calculation flow is shown in Fig. 11.

4.2 Case analysis

This paper takes a three span continuous rigid frame bridge as a case, and establishes the finite element model of the bridge. The specific parameters of the bridge are as follows: the total span of the bridge is 90m, each single span is 30m, the cross-section is box girder and the strength grade of concrete is C50. The piers are double thin-wall piers with the height of 20m. The sectional dimensions are shown in Fig. 12, the finite model of the bridge is shown in Fig. 13.

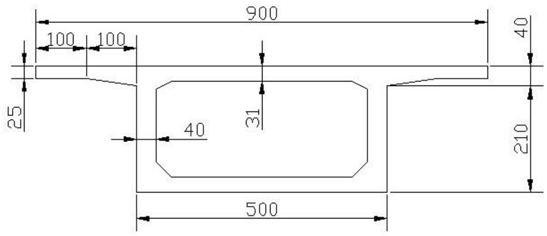


Fig. 12 Sectional dimensions

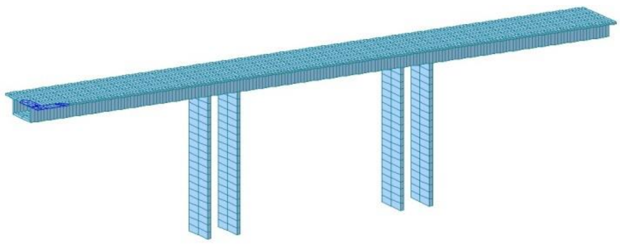


Fig. 13 The finite model of continuous rigid frame bridge

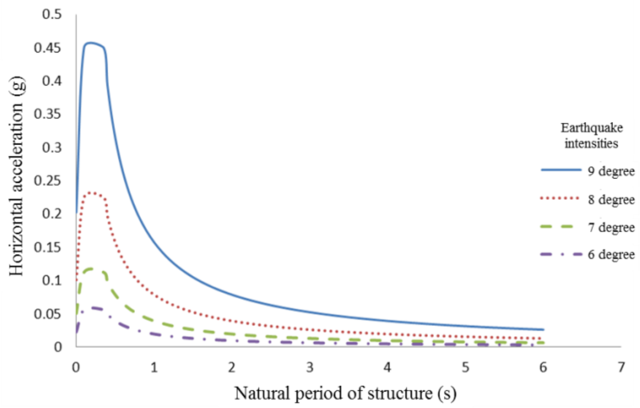


Fig. 14 Response spectrums under different earthquake intensities

Table 4 Stress-related damping ratios under different intensities

Seismic intensity	Horizontal acceleration (g)	Stress-dependent damping ratio (%)
6	0.05625	2.73
7	0.1125	2.86
8	0.225	3.09
9	0.45	3.43

The response spectrum method is employed for the seismic analysis of the bridge, the 6, 7, 8, and 9 degree seismic intensities are considered, respectively, the corresponding response spectrum curves are shown in Fig. 14.

The computed damping ratio is based on the structural damping ratio, combined with the stress-dependent damping ratio, and the fundamental structural damping ratio of the continuous rigid frame bridge is 2.5% (Li *et al.* 2014). The stress-dependent damping ratio of the bridge can be obtained by four times of iterative calculation, the calculated results under different seismic intensities are

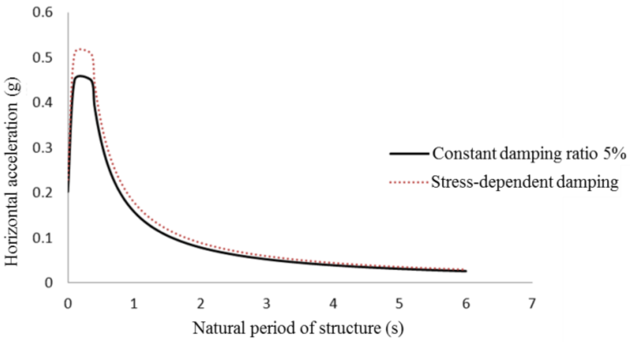


Fig. 15 Response spectrums with different damping models

Table 5 Calculation results with different damping models

Dynamic response of the pier	Constant damping ratio (5%)	Stress-dependent damping ratio	Error (%)
Displacement (mm)	96.136	108.809	+13.18
Shear force (kN)	432	489	+13.20
Bending moment (kN.m)	6458.32	7328.19	+13.47

shown in Table 4.

As shown in Table 4, the damping ratios of the bridge increase with the increasing of earthquake intensities. The calculated damping ratio is apparently less than 5% provided in China's Guidelines for Seismic Design of Highway Bridge (MOT 2008). In the design stage, setting a high value of damping ratio can lead a lower dynamic response, which is adverse for the safety of the structure.

In this paper, the response spectrums with the 5% constant damping ratio and the stress-dependent damping ratio are calculated, respectively, as shown in Fig. 15.

The dynamic response of the rigid frame bridge is calculated by two different damping models, the specific calculation results are shown in Table 5. The displacement of the top of the bridge's pier obtained by using stress-dependent damping ratio is significantly larger than the calculation results with the constant damping ratio.

5. Conclusions

In this paper, a cyclic loading experiment was conducted to study the effect of stress amplitude on the material damping of concrete. Furthermore, a modified seismic design and analysis method of bridge based on stress-dependent damping theory was proposed. The following conclusions can be drawn from the works:

- The experimental results show that the dissipate energy and storage energy of concrete decrease with the decreasing of stress amplitude, and the decreasing trend of the dissipate energy is lower than that of storage energy.
- The seismic responses of a bridge pier are calculated by using stress-dependent damping ratio and constant damping ratio (5%). The comparison of the top displacement of the bridge pier between the measured result and calculated results shows that the stress-dependent damping ratio application achieves much higher accuracy. In addition, by using the stress-dependent damping model, the damping ratio shows significant increment with the increasing of seismic intensity.
- The calculation of the actual damping values and dynamic response of the continuous rigid frame bridge under different earthquake intensities indicates that the seismic response obtained by using stress-dependent damping ratio is significantly larger than the results with constant damping ratio.

Meanwhile, this study still has some limitations and needs further improvement. Firstly, the energy dissipation of concrete was tested under uniaxial cyclic load in this paper, however, the stress conditions of concrete are complicated in the actual structures. Secondly, the stress-dependent damping theory is more applicable to describe the energy dissipation property of concrete in elastic stage. Finally, in order to introduce the material damping into dynamic analysis of structure, two assumptions are made in this paper, and further calculation and validation are required.

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