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Seismic safety of prestressed concrete cable-stayed bridges

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ABSTRACT: Elasto-plastic earthquake responses of two prestressed concrete (PC) cable-stayed bridges in Japan designed according to the current standard specifications have been analyzed. Attention has been directed to the total balance of structural members' safety factors against earthquakes, and reasonable safety factors reflecting plasticization have been considered. In considering the balance of safety factors, an importance factor for a member was defined in terms of changes in the vibration characteristics of the structure in the event of a cross-sectional failure, and this was compared with the safety factor.

1 INTRODUCTION

A considerable number of long-span prestressed concrete (PC) cable-stayed bridges have been constructed in recent years in many parts of the world. Although these structures have been designed on the basis of elastic analysis, the behavior of individual structural members is expected to enter the plastic range during large earthquakes. If cable-stayed bridges are to be rationally designed against large earthquakes, it is necessary to consider the elasto-plastic behavior of members as a part of seismic design.

Since PC cable-stayed bridges are highly statically indeterminate structures, stress redistribution in the plastic range is expected to affect the safety factors of members obtained from elastic analysis. If these structures are to be rationally designed for seismic loads, this stress redistribution should also be taken into consideration.

Directing attention to the safety factors of structural members against earthquakes and their overall balance, this paper discusses safety factors for structural members of actual PC cable-stayed bridges in Japan, reflecting plasticization, designed according to the current standard specifications. The total balance of safety factors for members was considered on the basis of the concept of a structural damage index, and an importance factor for a member is defined in terms of changes in the vibration characteristics of the structure in the case of cross-sectional failure of the member. The validity of the total balance of safety factors for structural members according to the current standard specifications is reviewed through a comparison of the importance factor and the safety factor.

2 SEISMIC RESPONSE ANALYSIS

A floating type bridge (whose girder and tower are not connected) and a rigid connection type bridge (whose girder and tower are rigidly connected), both typical forms of PC cable-stayed bridge in Japan, were chosen for analysis from among recent two-span continuous bridges built in Japan. Both bridges were designed according to the Specifications for Highway Bridges. First, cross sections were determined by the allowable stress design method to resist the design loads obtained from a linear analysis. Second, the ultimate strength against failure under the ultimate factored load, also obtained by linear analysis, was checked. Stress redistribution, therefore, was not considered.

Interaction between the girder, tower, stay cables and the pier of a PC cable-stayed bridge, as well as the influence of stress redistribution, is considered to be greater in the direction of the bridge axis than in the direction perpendicular to the bridge axis. So the analysis dealt with seismic motion along the bridge axis. Fig. 1 shows the analytical models used.

The Muto rule shown in Fig. 2(a) was applied to the bending moment-curvature relationship. During a large earthquake, the axial stiffness of stay cables was expected to decrease under the influence of sag caused by decreased tension. To model changes in this stiffness due to variation of axial force, the rule shown in Fig. 2(b) was applied.

Two patterns of acceleration response spectrum, as shown in Fig. 3, were used as seismic input waves for the analysis. One is that described in the Specifications for Earthquake Resistant Design of Highway Bridges with regard to checking the ductility of reinforced concrete structures (hereafter referred to as the "design spectrum"). This response spectrum is for seismic waves having predominant long periods, and the response spectrum starts to decrease at a natural period of 1.4 sec. The other is a smoothed spectrum obtained from strong motion acceleration data (hereafter referred to as the "observed wave spectrum"). The response spectrum was assumed to begin to decrease at a natural period of 0.3 sec. Artificial

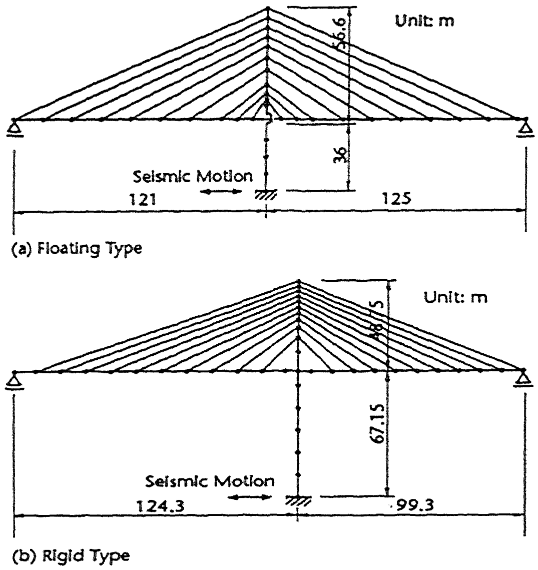

Figure 1. Analysis Models

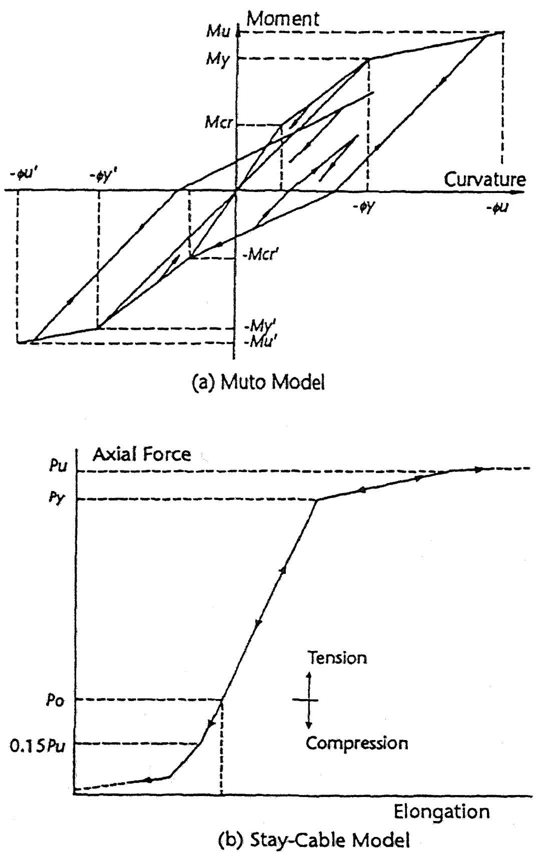

Figure 2. Hysteresis Rules

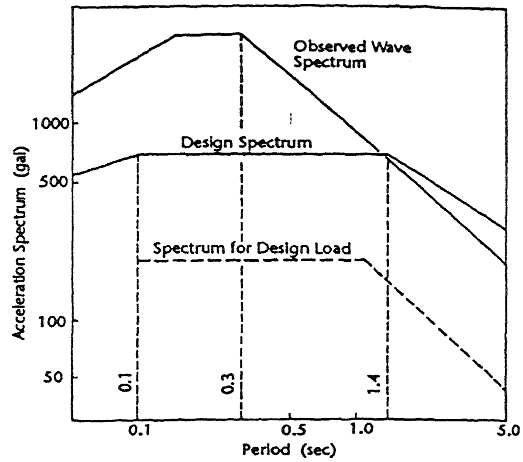

Figure 3. Response Spectra of Input Wave

seismic waves that fit these acceleration response spectra were obtained by adjusting amplitudes in the frequency domain for typical strong motion acceleration data (Kaihoku Bridge TR). The strength of seismic waves for the design spectrum was determined according to the Specifications, and the wave strength for the observed wave spectrum was adjusted so that values of the first to fifth mode responses, which are the predominant responses of the analyzed structures, became almost equal. Fig. 3 also shows, by broken lines, a spectrum used in the design of cross sections.

Elastic analysis and elasto-plastic analysis were performed using these seismic waves, and the results of the two analyses were compared.

3 INFLUENCE OF STRESS REDISTRIBUTION

Fig. 4 compares the distributions of bending moments obtained from the elastic and elasto-plastic analyses. The response values obtained from the elasto-plastic analysis were smaller than those obtained from the elastic analysis. This was due to increases of damping and extensions of natural period stemming from plasticization, that is, cracking and yielding. Since the forms of these distributions are quite similar, it can be concluded that stress redistribution in PC cable-stayed bridges is small and that failures do not tend to concentrate at certain cross sections during a large earthquake. This is presumably because the influence of decreases in stiffness does not pronouncedly affect the responses of other members due to the very high degree of redundancy.

4 RATIONAL MEMBER SAFETY FACTORS AGAINST EARTHQUAKE

4.1 *Balance of Safety Factors*

The results of the elasto-plastic analysis confirmed that the locations of cross sections shown in Fig. 4 that become

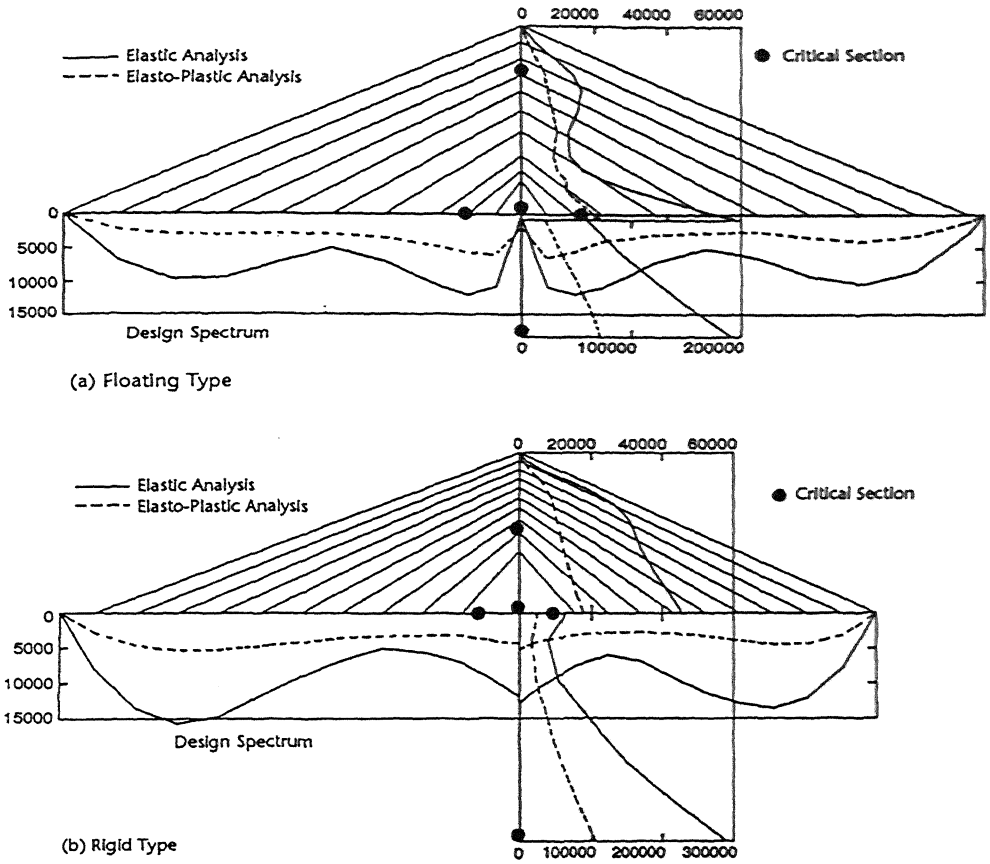

Figure 4. Stress Redistribution

critical during large earthquakes do not depend on the pattern of acceleration response spectrum for seismic waves. Such cross sections exist only in the girder near the connection with the tower, in the middle of the tower, at the bottom of the tower, and at the bottom of the pier. The maximum tension of stay cables turned out to be 80% or less of yield strength, which is deemed adequately safe. It is thought that the safety factors of stay cables, along with the influence of variable load, need to be reconsidered.

Safety factors of members and their balance have been considered for four concrete cross sections that become critical during large earthquakes.

Fig. 5 shows the safety factors of members defined as the ultimate moment of a cross section divided by the maximum response bending moment of the cross section. It is considered that these safety factors, which range between 1.2 and 1.0, are well balanced. This is to be expected since the safety factor according to the current standard specifications is based on the relationship between the ultimate moment and maximum response bending moment of the cross section, just as defined here. Additionally, although the calculation of that safety factor is based on elastic analysis, the difference between the patterns of response distribution obtained from elasto-plastic analysis and linear analysis is small due to the small influence of stress redistribution.

When considering seismic damage to a cross section, it is necessary to take energy absorption, rather than bending moment, into consideration. As a simple indicator of energy absorption, a ductility ratio defined as the maximum response curvature of a cross section divided by

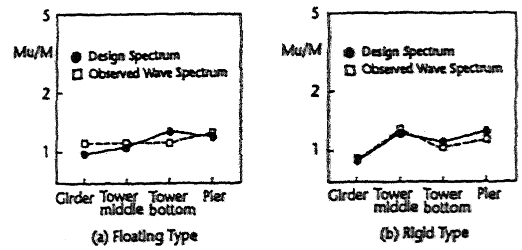

Figure 5. Safety Level by Bending Moment

yield curvature was used in calculating the safety factor. Safety factors for different members thus obtained were compared.

As shown in Fig. 6, the safety factor defined as the ultimate ductility ratio of a cross section divided by the maximum response ductility ratio of the cross section varied widely among members. The safety factor for the bottom of the pier is high. This is considered to be related to the fact that in Japan members with large cross sections and low reinforcement ratios have traditionally been used in substructures. Such members are less likely to suffer spalling of concrete and resultant decreases in axial strength, thereby minimizing earthquake damage.

4.2 *Definition of the Importance Factor and Comparison with Safety Factors*

In order to quantify the importance of structural members, it is necessary to consider various factors, such as influence for structural failure, difficulty of repair, and the influence of the possible damage on society. However, it is impossible, at the present state of technical knowledge, to quantify all of these factors. In this paper, attention has been directed to the changes in vibration characteristics of the structure in the event of failure of a cross section.

Fig. 7 shows the principle natural vibration modes for the analyzed structures. In both structures, the first mode is a mode in which displacement along the bridge axis (sway of the girder) is predominant, and this results in bending deformation of the tower. The second mode is a mode in which bending deformation of the tower and bending deformation (vertical vibration) of the girder are coupled through stay cables. According to the response spectrum method, response values of bending moment in these two modes account for more than 70% of the total.

These vibration modes indicate that in the girder, even if a hinge forms after the ultimate failure of a cross section, it does not have a major impact on the vibration characteristics of the entire structure. The structure will remain stable and will not collapse as long as the stay cables are sound. A hinge that forms at the bottom of the tower should not greatly affect the rigid connection type bridge because deformation at the bottom of the tower is constrained by stay cables. By contrast, in the floating type bridge, a hinge at the bottom of the tower will considerably affect the second mode in which bending deformation of the tower predominates. Since the bottom of the pier alone supports the superstructure, the ultimate failure of a cross section here has a catastrophic effect on the strength of the entire structure.

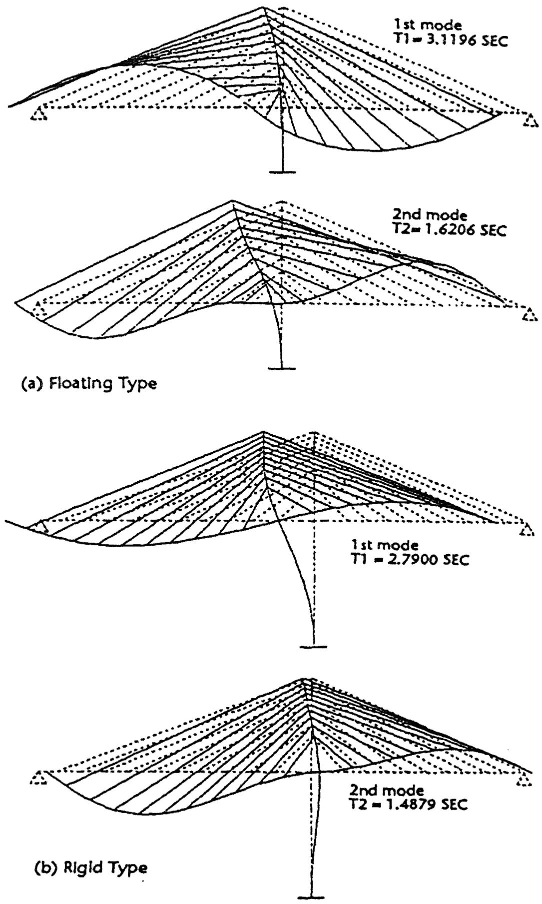

Figure 7. Natural Vibration Models

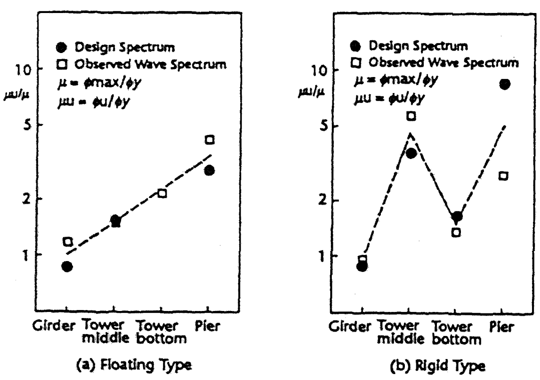

Figure 6. Safety Level by Ductility

One way to quantify such influences for structural failure is to introduce the concept of a structural damage index which is used to express the degree of damage to the entire structure.

In view of the fact that the stiffness of structures that suffer earthquake damage decreases, and hence natural periods become longer, Cakmak et al. (1989) proposed a structural damage index defined in terms of a maximum softening ratio δ.

$$\delta = 1 - (To/T\max)$$

where,

To : natural period of undamaged structure

Tmax: maximum natural period during earthquake of damaged structure

Assuming that the four cross sections that become critical during large earthquakes have failed, the natural periods of a structural model having a hinge in each of the four cross sections were calculated to investigate changes in the maximum softening ratio. Since a PC cable-stayed bridge is a multiple-degrees-of-freedom system, the contributions from the various modes to the vibration characteristics were considered in terms of the square root of the sum of the square of the contribution from each mode, which is generally evaluated in modal analysis by means of response spectrum. Thus, the importance factor ω_m of member m was defined as follows:

$$\omega_m = \sqrt{\Sigma(\beta_{mi}\,\delta^2_{mi})}$$

where,

$\delta_{mi} = 1 - T_{oi}/T_{mi}$: maximum softening in the i th mode

T_{oi} : period in the i th mode of a model without hinge

T_{mi} : period in the i th mode of a model with a hinge in member m

β_{mi} : participation factor in the i th mode of a model with a hinge in member m

Since earthquake responses of the analyzed structures are mostly governed by contributions in the first to fifth modes, vibration up to the fifth mode only was considered. Fig. 8 shows the importance factors of the members analyzed. In the figure, the importance factor of the girder is normalized at 1.0, and the relative importance of other members is shown accordingly. The importance factor for the bottom of the pier turned out to be highest, indicating that the failure of its cross section has the greatest impact on the entire structure. It is noteworthy that the relationship between the importance factor for the middle of the tower and that for the bottom of the tower varies depending on the type of structure. This is because the critical section in the middle of the tower in the floating type bridge is at a higher position than that of the rigid connection type, and hence changes in vibration characteristics of the structure due to a hinge forming there are smaller in the floating type than in the rigid connection type. It is also because at the bottom of the tower in the rigid connection type bridge, the lowest stay cables constrain the deformation of the tower, as mentioned earlier. This means that the bottom of the tower in a rigid connection type bridge is less important than in a floating type bridge.

Fig. 9 compares the member importance factor with the member safety factor defined in terms of the ductility ratio. As shown, more important members have higher safety factors, showing a good agreement in balance between the importance factor and the safety factor. It can be concluded, therefore, that member safety factors as defined in terms of the ductility ratio well reflect the balance of member importance factors of the analyzed structures.

Only a limited number of investigations into the quantification of the importance factors of structural members have been reported so far. This study has confirmed that by applying the structural damage index, the influence of the failure of members for the collapse of the entire structure can be quantified as the importance factor of those members. It has also been confirmed that PC cable-stayed bridges that are designed according to the current standard specifications have well-balanced seismic safety factors, which make for adequate resistance to large earthquakes.

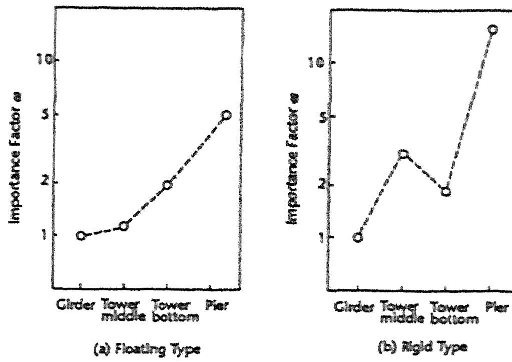

Figure 8. Member Importance Factor

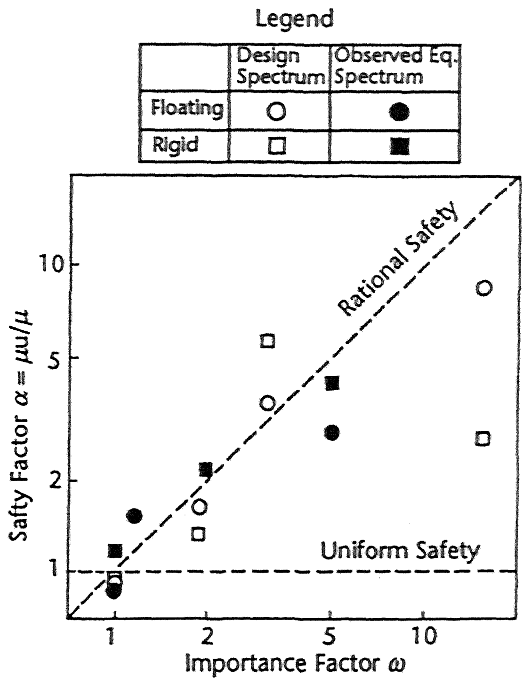

Figure 9. Comparison of Safety Factor with Importance Factor

5 CONCLUSION

Elastic and elasto-plastic analyses were performed for two *types of cable-stayed bridges to investigate the maximum* response, patterns of response distribution, and safety factors of members and their total balance.

The influence of stress redistribution in these structures is small. During large earthquakes, major failures tend to occur in the girder near the connections with the tower, in the middle of the tower, at the bottom of the tower, or at the bottom of the pier. If the member safety factor is defined in terms of the maximum response bending moment in a cross section, safety factors at these locations are similar. If the member safety factor is defined in terms of the ductility ratio of a cross section, then safety factors vary widely from member to member. The safety factor for the bottom of the pier, where failure is considered to be catastrophic to the entire structure, turned out to be rather high.

It was assumed that the importance of a structural member can be expressed in terms of the influence of the member's failure for the collapse of the entire structure. An importance factor for a member has been defined by investigating the natural period of a structural model that has a hinge in a cross section of that member. Comparison of the member importance factor and the member safety factor as defined in terms of the ductility ratio revealed that the balance of safety among members agrees well with the balance of the importance of members defined here. It has been confirmed, at least from one viewpoint, that PC cable-stayed bridges designed according to the current standard specifications have well-balanced safety factors against large earthquakes.

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