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Assessment Procedure for Buckling of Thin Walled Cylindrical Liquid Storage Tanks in Nuclear Power Plants under Seismic Loading (2nd Report ;Proposal for Reasonable Seismic Design Guideline Taking Dynamic Response Reduction Factor into Account)

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ABSTRACT

The current elastic design guideline for thin walled cylindrical liquid storage tanks in nuclear power plants against seismic loading might result in too conservative component design as compared with elasto-plastic design in general industries. Considering dynamic response reduction, it is thought possible to make the design guideline more reasonable. In this series of study, experiments using scaled models were carried out, and seismic behavior of thin walled cylindrical liquid storage tanks was simulated to investigate energy absorption capacity and seismic resistance of those tanks.

In this 2nd report of series of studies, seismic behavior of tanks was simulated to estimate a dynamic response reduction factor. This factor is based on the energy absorption capacity of structures. Through experiments and numerical study, a response reduction factor with aseismic margin to design thin walled cylindrical liquid storage tanks has been proposed.

KEY WORDS: cylindrical liquid storage tank, nuclear power plant, elasto-plastic design, energy absorption capacity, dynamic response reduction factor, aseismic margin

1. INTRODUCTION

The design method with safety factor for buckling is applied for designing thin-walled cylindrical liquid water storage tanks. This method is described in Technical Guideline for Aseismic Design of Nuclear Power Plant (Japan Electric Association Guideline No.4601:JEAG4601). This guideline has possibility to be made more reasonable by taking real buckling phenomenon into account. On the other hand, in ASME code Appendix XIII-1551, buckling evaluation in plastic area is mentioned. But it is not concrete to estimate stress of buckling. And in ASME code case N-284, stress evaluation way is mentioned in detail. But it does not consider the effect of plastic deformation. For F.B.R., a guideline considering real buckling phenomenon is provided. In this evaluation method of buckling, dynamic response reduction factor by plastic deformation before buckling is adopted. And in Design Recommendation for Water Storage Tanks and Their Supports by Architectural Institute of Japan provides an evaluation method of buckling considering energy absorption by plastic deformation after buckling. In this report, analysis which corresponded to experiments(shown in 1st report) and the advanced evaluation method for buckling is proposed based on experimental data(shown in 1st report) and analytical data(obtained in this report).

2. INVESTIGATION for DYNAMIC RESPONSE REDUCTION FACTOR

Buckling evaluation method proposed in this report, dynamic response reduction factor D_S obtained by plastic deformation is adopted. D_S is estimated to use evaluation method for D_S mentioned in AIJ by experimental and analytical data.
Several values of D_S are obtained from each test and analysis. For using elasto-plastic design, D_S is a fixed value and called " ${}_DD_S$". The way to decide ${}_DD_S$ is shown in following (1)~(8).

(1)Grasp of characteristic of relationship between stress and deformation

The relationship between acceleration and displacement of cylinder top obtained by Dynamic buckling tests using large scaled models and static buckling analysis shows in figure 2.1-1 and 2.1-2. The point where acceleration comes up to maximum value is defined as buckling point. Displacement of cylinder top is 2.6mm at buckling point and 11mm at critical condition (water leakage occurred). Both values are only beam deformation component. Large scaled models are one fifth of analytical models (shown in 1st report). Compare the horizontal axis Fig. 2.1-1 and 2.1-2, displacement of cylinder top Fig. 2.1-1 is one-fifth of Fig. 2-1-1.This result gives good agreement with similarity low. On the other hand, for vertical axis, it is able to compose Fig.2.1-1 and Fig2.1-2 by considering effective mass. Acceleration of cylinder top multiplied by effective mass equals base loading. But it is not good agreement with similarity law because correct estimation of vibrational characteristic of tanks varying with plastic deformation is impossible. As a precondition to adept dynamic response reduction factor,it is necessary that sudden loss of load and deformation capacity never occurs after buckling. Result of tests and analysis up to the ultimate condition shows that enough load and deformation capacity remains, and as the displacement of cylinder top increases, dropping ratio of the load and deformation capacity decreases. Therefore, liquid strange tanks are considered to satisfy the above-mentioned precondition.

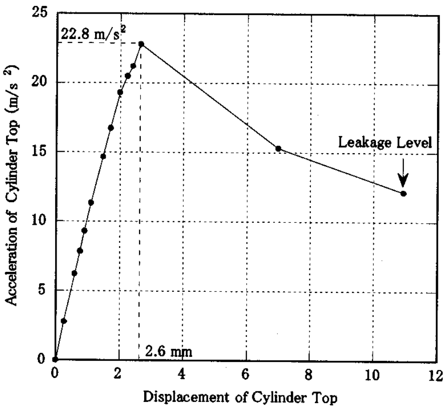

Fig.2.1-1 Displacement and acceleration of cylinder top obtained by test

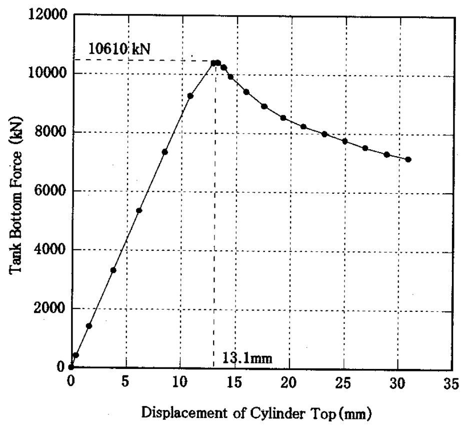

Fig.2.1-2 Displacement and acceleration of cylinder top obtained by analysis

(2)Grasp of Critical Condition

Dynamic buckling tests was operated various seismic level (seismic level gradually increased). Tank wall was cracked at certain seismic level. Crack was occurred in elephant foot bulge portion. From this fact, it is considered that allowable limit condition can be estimated by deformation and strain of elephant foot bridge portion.

(3)Establishment Allowable limit and deformation for bucking

The relationship between displacement of cylinder top and residual deformation of elephant foot bulge area obtained by

Dynamic buckling tests and analysis is shown in Fig.2.1-3 and 2.1-4. In Fig.2.1-3 residal deformation of elephant foot bulge was 16mm at critical condition. Now, allowable limit condition is established to adopt AIJ way for dynamic response reduction faster D_S with 0.01R, considering the fabrication tolerance of cylindrical liquid storage tank resided deformation limit is 0.012. Adopting this limit for tests and analysis displacement of cylinder top is 8.2mm (shown in Fig.2.1-3) and 33mm (shown in Fig.2.1-4).

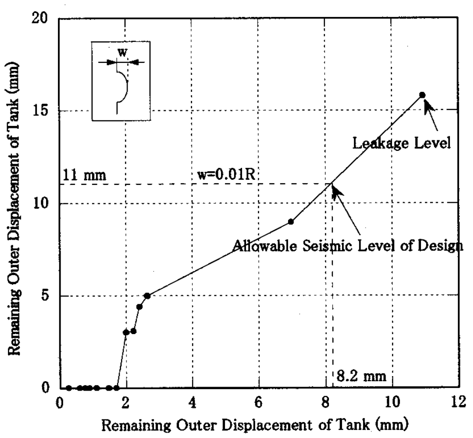

Fig.2.1-3 Displacement of cylinder top and residual deformation of elephant foot bulge obtained by test

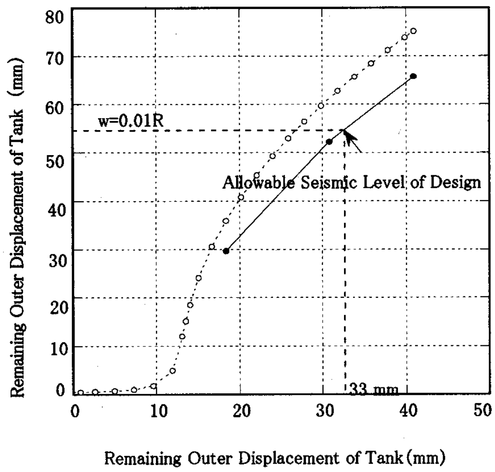

Fig.2.1-4 Displacement of cylinder top and residual deformation of elephant foot bulge obtained by analysis

(4)Evaluation of the critical limit factor

Now, calculate the critical limit factor ì which is one of the essential parameters to calculate dynamic response reduction factor D_S according to AIJ method. ì is the evaluation factor to use displacement of cylinder top value for margin buckling level to allowable limited condition. The definition as follows

$$\text{ì} = \frac{\text{Displacement of allowable limit level}}{\text{Displacement of buckling level}} - 1$$

To use displacement of allowable limit level, ì is 2.15 and 1.52 for tests and analysis.

(5)Confirmation of local strain and examination of fatigue strength

Pointing out local strain of elephant foot bulge area because tank axis strain at inner surface is larger than that of outer surface. So strain shall be inner surface. To confirm the range of strain obtained by repeat load, result of two-direction loading analysis is shown in Fig.2.1-5. Amplitude of loading is 40mm. 40mm is larger than 33mm which is allowable limit displacement. Limit fatigue repeat number of stainless steel 304 is 3000(low cycle fatigue). On the other hand,equivalent fatigue repeat number of input seismic wave is 43 (Calculation method based on JEAG4601). This number is smaller than limit number 3000.(fatigue damage factor Df=0.014) As mentioned, at allowable limit condition, there is enough fatigue strength in elephant foot bulge area.

(6)Calculation of load reduction Factor

Load reduction Factor q is standing up loading at allowable limit condition divided by that of maximum value. To use skelton curve Fig.2.1-1 and Fig.2.1-2, q is 0.63 and 0.66 for test and analysis.

(7)Estimation dynamic response reduction factor D_S

AIJ method is adapted to calculation dynamic response reduction factor D_S for skelton curve obtained by tests and analysis. On this occasion, q is used at allowable limit point value.Fig.2.1-6 shows D_S=0.42 for ì =2.15 and =0.63. In the same way, D_S=0.43 for analysis. For another test and analysis, each D_S equals to 0.39 and 0.45.

(8)Establishment of dynamic response reduction factor for design $_{D}D_{S}$

According to D_S obtained by test and analysis 0.39～0.45 $_{D}D_{S}$ was established 0.5.

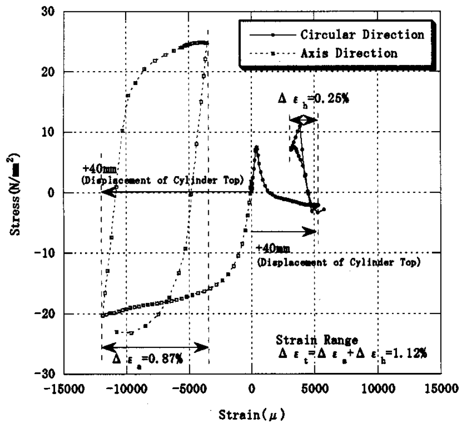

Fig.2.1-5 Strain and stress of elephant foot bulge

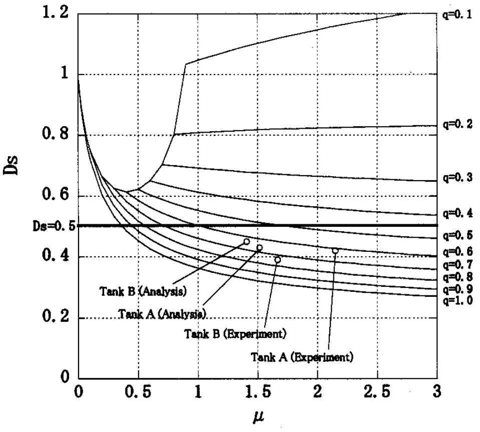

Fig.2.1-6 Relationship between Resistance Force Reduction and Allowable displacement factor in AIJ guideline and Allowable displacement factor and D_S in AIJ guideline

3. EXAMINATION of ASEISMIC MARGIN

Operating non-linear seismic response analysis by using single-degree of freedom system model, we evaluate aseismic margin of liquid storage tank designed by $_{D}D_{S}$ =0.5 which is established in 2nd paragraph has good aseismic margin or not. Furthermore, aseismic margin was estimated by using test result and evaluate d real aseismic margin value of tanks.

3.1 Evaluation of aseismic margin

(1)Definition of aseismic margin

Aseismic margin definition as follows

$$\text{aseismic margin} = \frac{\text{Allowable limit seismic level}}{\text{Design seismic level}}$$

Allowable limit seismic level: seismic level for allowable limit Design seismic level: seismic level for design input.

Each relationship between aseismic level and aseismic level shows in Fig.3.1-1. This figure shows that aseismic margin indicates. Aseismic margin which defines above shows margin to allowable limit seismic level. This margin is to allowable limit seismic level.

(2)Outline of seismic response analysis

Seismic response analysis uses single-degree-of-freedom system no-linear mass damping model. It is assumed that hysteresis diagram (Fig.3.1-2) shows seismic response characteristic of liquid storage tank properly.

3.2 Evaluation of analysis correspond to test

In this paper, the following seismic response analysis is operated to examine applicability of seismic response analysis. Simulate the test by seismic response analysis it is not impossible to consider damping various effect to simulate test by analysis because it is impossible to simulate the non-linear oval vibration which occurred upper part of cylinder in tests. So evaluation aseismic margin obtained by analysis is more conservative than that obtained by analysis.

3.2.1Analysis condition

a. skelton curve

Skelton curve was decided by acceleration curve at cylinder top obtained by tests. Effective mass height and effective mass weight was decided by AIJ guideline, and replaced the test with equivalent single-degree-of-freedom system model. Skelton curve of tank A obtained by large-sealed model shows in Fig.3.2-1.

b. Damping

1% based damping and hysteresis damping was considered as effect of damping.

c. Result of analysis

Fig.3.2-2 shows the relationship between input seismic level and response displacement in dynamic buckling test and seismic response analysis. This figure shows result of analysis gives conservative evaluation comparing with that of test.

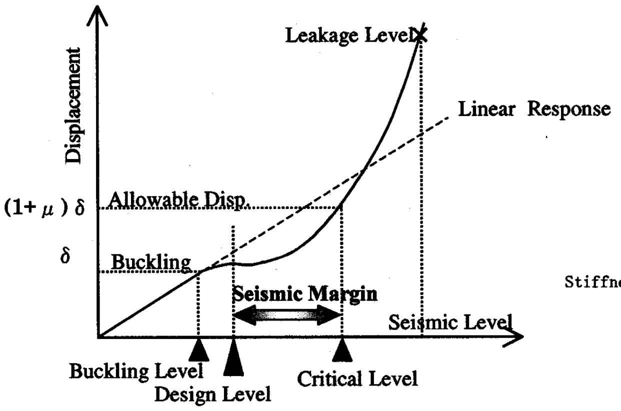

Fig.3.1-1 Conceptual figure of input seismic level and aseismic margin

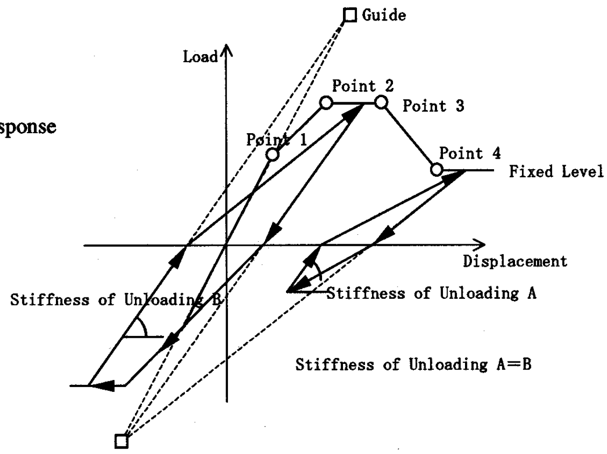

Fig.3.1-2 Conceptual figure of hysteresis low

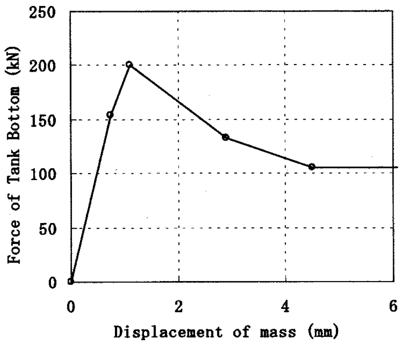

Fig.3.2-1 Example of skelton curve obtained by test

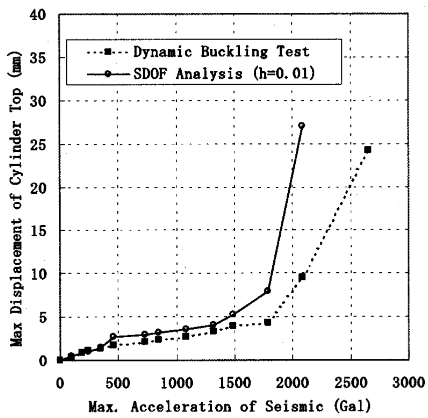

Fig.3.2-2 Comparison dynamic buckling test and seismic response analysis

3.3 Evaluation aseismic margin of tank which is designed by Ds=0.5.

It is evaluated for ideal tank which is designed by using ${}_{D}D_{S}$=0.5(buckling when input seismic level is design input seismic level) to estimate the conservation of dynamic response reduction factor ${}_{D}D_{S}$=0.5 which was examined paragraph 2. Ideal tanks are objected two kinds of tank which were used in calculation dynamic response reduction factor.

3.3.1 Analysis condition

a. input seismic wave

For analysis, seismic wave for evaluation was input wave. Response spectrum curve of evaluation wave shows in Fig.3.3-1.

b. Skelton curve

Skelton curve defines as relationship between load and displacement of cylinder top obtained by static buckling analysis. Analysis model is No.1 and No.2 tank (shown in 1st Report) load reduction factor q is established q=0.6.

c. Damping

1% based damping and hysteresis damping was considered as effect of damping.

3.3.2 Examination applicable of Ds calculation formula in AIJ guideline

Ds calculation formula in AIJ guideline is based on assumption that deformation of tank groves both side equally. But in fact, it is considered the deformation of tank lean to one side. So it needs to confirm the applicability of this formula , the Compare results of non-linear seismic response analysis that is possible to reappear of leaning deformation, it is confirmed to applicability of formula. It is compared that result of Ds-ì curve in AIJ guideline and that of seismic response analysis is indicated in Fig.3.3-2. This figure that result of seismic response analysis is lower value than Ds-ì curve in AIJ guideline, and it is confirmed applicability of Ds-ì curve.

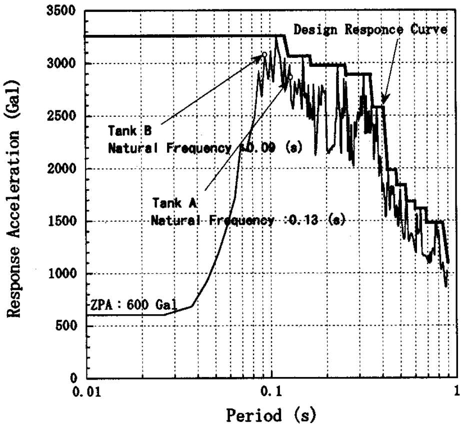

Fig.3.3-1 Input seismic response spectrum

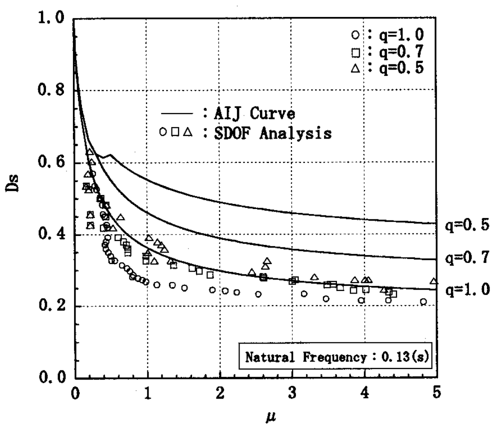

Fig.3.3-2 Comparison Ds-ì curve in AIJ guideline and that of seismic response analysis

3.3.3 Evaluation of Aseismic Margin

(1)Result of analysis

In Fig.3.3-3, result of seismic response analysis of No.2 tank is shown. It is shown maximum displacement of cylinder top for input level (maximum acceleration) using seismic wave for evaluation.

(2)Aseismic margin

It is evaluated for aseismic margin to use allowable limit factor ì estimated by examination of dynamic response reduction factor. In the same way, aseismic margin is 1.52 for No.1 tank. For both case, aseismic margin is more than 1.5. As mentioned, liquid storage tank which is designed by $_{D}D_{S}$=0.5 has aseismic margin more than 1.5 for seismic wave.

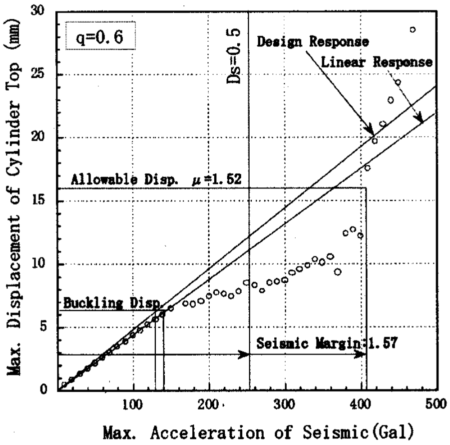

Fig.3.3-3 comparison Ds-ì curve in AIJ guideline and that of seismic response analysis

4. BUCKLING EVALUATION FORMULA CONSIDERING DYNAMIC PESPONSE REDUCTION FACTOR

In paragraph 2 and 3, $_{D}D_S$ is 0.5 is indicated to secure enough margin. In following, buckling design formula is proposed.

4.1 Application Condition

Proposed buckling evaluation method is for liquid storage tanks which have following structure and operated under following condition. And it is examined to apply this guideline by tests or other methods, it is possible to use this guideline out range of following conditions.

(1)Structure

Vertical circular liquid storage tank fixed to the foundation by anchor bolts

(2)Range of size

$100 \leqq R/t \leqq 1100$

bending buckling area size limit $100 \leqq R/t \leqq 900$

$100 \leqq R/t_m \leqq 900$

$1.4 \leqq L/R \leqq 4.0$

R =Inner Diameter

t =plate thickness

t_m =average body plate thickness

L =cylinder height

4.2 Input seismic Acceleration

(a)If natural frequency of water storage tank is smaller than that of input seismic spectrum peak, input seismic acceleration is spectrum value as it is.

(b)If natural frequency of water storage tank is larger than that of input seismic spectrum park, seismic acceleration is spectrum peak value.

4.3 Dynamic response reduction factor D_S

for buckling evaluation, the value of Ds is defined as following

for seismic wave S_1 :0.5

for seismic wave S_2 :1.0

dynamic response reduction factor Ds is reduction factor of operating force according to horizontal seismic acceleration. And if it is possible to separate liquid pressure due to vibrational mode the dynamic liquid pressure according to horizontal wave, it is able to take dynamic response liquid pressure evaluation for allowable stress. For evaluation of primary stress, dynamic response reduction factor Ds is applied.

4.4 Guideline Formula

It is evaluated for axis compression buckling and bending buckling to consider interaction with each other. Shear buckling is judged independently from axis compression buckling and bending buckling. Dynamic response reduction factor Ds is applied for the stress due to horizontal seismic acceleration.

Evaluation formula for bending and axis compression loadings

$$\frac{\sigma_c}{{}_c\sigma_{cr}} + {}_DD_S \frac{\sigma_b}{{}_b\sigma_{cr}} \leqq 1$$

Evaluation formula for shear loading.

$${}_DD_S \frac{\tau}{\tau_{cr}} \leqq 1$$

σ_c	: operating axis compression stress	${}_c\sigma_{cr}$	: allowable axis compression stress
σ_b	: operating bending stress	${}_b\sigma_{cr}$	: allowable bending stress
τ	: operating sear stress	τ_{cr}	: allowable shear stress

CONCLUSION

In this study, we analyzed cylindrical liquid storage tanks against seismic load corresponding to dynamic buckling tests (shown in 1st report). And it is proposed the advanced guideline for buckling. The following conclusions were obtained.

(1) To use characteristic of liquid storage tanks obtained by test and analysis, dynamic response reduction factor for liquid storage tank is 0.39～0.45 based on D_S-ì curve in AIJ.AIJ method is conservative method because D_S obtained by test is smaller than that of this value.

(2) Dynamic response reduction factor for design was established 0.5.

(3) To compare D_S-ì curve in AIJ and result of seismic response analysis, it is confirmed that dynamic response reduction factor obtained by Ds-ì curve in AIJ is conservative.

(4) Operating non-linear seismic response analysis by single-degree-of-freedom system model, it is evaluated aseismic margin for imaginary tank which was designed by using ${}_DD_S$=0.5. As a result, it is confirmed that tanks which is designed by using ${}_DD_S$=0.5 has enough aseismic margin more than 1.5.

(5) Design procedure which use dynamic response reduction factor for design ${}_DD_S$=0.5 was proposed.

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