ON FUNDAMENTAL CONCEPT OF ANTI-EARTHQUAKE DESIGN OF EQUIPMENT AND PIPINGS

H. SHIBATA
Institute of Industrial Science, University of Tokyo,
22-1, Roppongi 7, Minato-ku, Tokyo 106, Japan

M. KATO
Japan Atomic Power Company, 6-1, 1-chome Ohtemachi, Chiyoda-ku, Tokyo 100, Japan

This paper deals with a new concept of anti-earthquake design of equipment and pipings in nuclear power plants. Usual anti-earthquake design of such items starts from the design basis ground motions, via floor responses and ends at the stress analysis of each structural element. However, the same type of equipment are used for plants under various site conditions. The ordinarily used method obliges the repetition of such design procedure on each plant. This new design method has been developed to avoid such time-consuming repetitions.

The authors presented two papers in SMiRT-3 and 4-SMiRT. The former paper was on the " mode of failure " of items in NPP, and the latter one was on their proving test. Through the discussion for establishing their failure modes and the proving test procedure, the concept of the new design method which will be described was come out, and has been developing for the project of the standardization of anti-earthquake design procedure promoted by the Ministry of International Trade and Industries of Japan.

The new method consists of two-flow combination; one flow starts from the design basis ground motions and ends at the floor response spectrum, and the other flow starts from their allowable limits, mostly allowable stress, and ends at the allowable limit spectrum or the critical floor response spectrum of each type of them. This allowable limit spectrum or the critical floor response spectrum can be obtained through either design analysis or type approval testing of each type of a new item one. These curves can be said to be fragility response curve also.

The method can be expanded in the following three stages; that is

i) the critical limit force method.
ii) the critical seismic coefficient method.
iii) the critical floor response curve method.

If an item is very rigid, then it might be failed at some elements, like its legs, nozzles and so on, under the critical seismic load. In this case, we can calculate the reaction forces at every legs, nozzles and other connecting elements. This might be called " Critical Limit Force " and actually this load can be expressed by the critical external force vector.

A seismic coefficient, which gives the severest external force vector, can be defined as " Critical Seismic Coefficient ". If an item is not rigid, in a resonating region, the exciting floor motions should be lower than those in other frequency regions. It makes a notch on the uniform critical floor response curve which has a constant value equal to the seismic coefficient. Although the use of such critical floor response curve, that is, most of part is constant and equal to the critical seismic coefficient, it has several notches at the corresponding frequencies of eigen-frequencies of the item. This is " Critical Floor-response Curve ". Those three critical values have the corresponding allowable limit values using for the design.

The merit of these method is this, that is; one computation or testing is enough to decide such criteria. And only thing, we should do for a new plant, is to calculate the floor responses of each levels of the building, and to compare the allowable limit value to this result. We can eliminate huge amount of stress analysis of equipment and pipings of the new plant. The three methods should be selected according to the dynamic characteristics of the related items.

1. Introduction and Fundamental Concept

This paper deals with a scope of a new design method of earthquake-resistant equipment and piping systems in relation to the standardization of overall nuclear power station design. In Japan, the Ministry of International Trade and Industry is promoting the standardization. Along this line, the authors will discuss what is the standardization of anti-earthquake design of equipment and piping systems.

There are two main design methods; " one-through design method " and " counter-input design method ". Most of anti-earthquake design of equipment and piping systems in present time are " one-through method ". Several ideas belonging to " counter-input design method " are employed in actual design both in Japan and the United States; for example, the procedure for Class I Electrical Equipment described in IEEE Standard, design of nozzles of a pressure vessel and other equipment, design of casing of a valve and a pump and so on. Also the concept of qualification test is along this line. The authors will try to reorganize these ideas to a new design procedure in this paper.

We should discuss on the following problems for this purpose: What kind of procedures is using for the design? What kind of criteria is using for the design? How many levels of standardizations of anti-earthquake design can we list up? The authors want to put the discussion also on assurance of the functions of active component behind the discussion on the strength.

Most of design of equipment and piping systems are done based on allowable stress criteria. In other words, this is " safety factor design ". If we try to look at the history of a structural design, it is clear that we started to design structures and vessels as they have adequate proportions and configurations according to their engineering experiences. We might call such procedure as " proportional design ". When we are discussing the design in the view point of their strength against earthquake loadings, or such natural loadings, we should define the design basis event. Allowable stress and dbe are in a relative relation. Even though we employ very high level's dbe, we can mitigate the impact by employing rather high level's allowable stress like those for Faulted Condition in ASME Section III. Japanese Building Code employs the criteria of " elastic limit " against the seismic coefficient of 0.2. In early 1930's, they estimated that the peak acceleration of Kwanto earthquake-1923 might be 0.3 G. So they designed the code to satisfy the criteria; structures should survive against earthquake weaker than the level of Kwanto earthquake. Ultimate strength of reinforced concrete is approximately three times of its elastic limit, then " ultimate strength against 0.3 " was converted into " elastic limit against 0.1 ". Afterwards the quality of reinforced concrete was improved very much and elastic limit became almost twice. At that time it was considered that this modification should not be applied to the relation above-mentioned in the engineering view-point, and the figure of 0.1 was doubled to 0.2. This design practice can be applicable to other designs against natural loadings, and may be called as " nominal loading design ".

Recently we often use finite element method for the design analysis. The values obtained through such numerical computation should have high accuracy against given external and internal loadings. However, some external loadings such as earthquake loadings have very high uncertainties1) 2) both in defining process of dbe and in process of response analysis. Therefore, the meaning of such numerical computation by using very fine meshed model remains only to know fine stress distribution under an assumption of elastic state, and is not effective to know their absolute values.

There are several design methods more. The following discussion is based on such view point, that is, the design against natural events should be made based on design basis events defined under some assumptions and their allowable conditions. We can mention five stages of the ways of standardization of anti-earthquake design methods. Here the authors do not refer to the details of them. Some of them seems to be difficult to apply in Japan. So the development of equipment and pipings design standardization may be a realistic approach to this subject. They consider that " Counter-input design method " is a suitable method as the design procedures for this purpose.

2. Counter-input Design Method

This method may be called as " endurance limit design ", which came from endurance limit test. The philosophy of endurance limit test or type approval test[3)] was established for the space technology in early 1960's. The conventional anti-seismic design of equipment and piping systems starts from deciding DBE at the basement of the supporting building or in the free field. Then calculating the motions of their mounting floor, and making their response analysis, the response of equipment or pipings can be obtained. According to acceleration distribution on the object structure, the stress distribution on the system can be obtained, and their stress values should be lower than the corresponding allowable stress limits. This is " One-through design method ". Almost of all design of equipment and piping systems are designed in this way, however, even if the type of the particular equipment is completely same, the whole design procedure should be excised for every new power stations at the different site condition. This is an extreme waste of time and money. To avoid such wastes, counter-input design should be employed. As already we know, if a type of equipment has been passed through its endurance limit test to a certain pre-defined level of input ground motions, all equipment can be used on the floors, whose vibratory motions based on DBE are less than the pre-defined level, without individual stress report. Therefore, if we establish the file of all equipment for the standard plant, we can save the time and money for their anti-earthquake design.

2.1 Concept

If we consider on a single mass and spring system, and local stress of the critical point of supporting spring, it is easy to explain this method. Here, σ_a : the allowable stress of the material of the supporting member, σ_s : the seismically induced stress by DBE at the point, σ_n : the normal stress at the point, α_{dbe} : the value for the design at DBE, for example, the peak ground acceleration, α_l : the allowable limit input for the system. The limit value can be obtained by the equation

$$\alpha_l = [(\sigma_a - \sigma_n) / \sigma_s] \alpha_{dbe} \quad . \qquad (1)$$

In this paper and the other paper which will be presented in K2/6, the authors use the following notations; $\alpha = (\sigma_n + \sigma_s)/\sigma_a$ and $\beta = \sigma_s/\sigma_a$, then the equation (1) can be written as

$$\alpha_l = [(1 - \alpha + \beta)/ \beta] \alpha_{dbe} \quad . \qquad (1')$$

An example of the distributions of stress on a main steam piping at points adjacent to valves is shown in Fig. 1. The straight lines drawn with parameters n have the margin for the fluctuation of seismic induced stress. The meaning in the probabilistic view point will be discussed later. Defining a parameter η as follows from eq. (1')

$$\eta = [1 - (\alpha - \beta)] / \beta \ . \qquad (2)$$

This relation becomes as Fig. 2. From the values α and β in the case of Fig. 1, (0.52, 0.29) at the point A is the most critical point. If we assume that the starting DBE in this case is 0.2 G, then α_l might be 0.53 G. The point B; (0.73, 0.16) is also one of the critical points as well as the point A. Other three points between two points in Fig. 1 are almost same, that means, the design of this piping is well balanced one.

2.2 Flow of Design

A simple example was described in the previous section using the values of α and β. This means that we need the response and stress analysis under an assumed DBE condition. And by the comparison to the allowable stress we obtain the allowable limit input. The example of the previous section remains only on the primary stress based on USAS B 31.1, however, if we employ B 31.7 / ASME Sec. III, we should consider on Pm, PL + Pb, $(PL + Pb + Q)_E$ and fatigue criteria. Usually Pm induced by earthquake is not significant, so we can eliminate this effect except some special cases like a piping bridged between two structures.

The flow chart of actual procedures is shown in Fig. 3. This flow chart shows only the force balancing part of the procedure, which is the extension described in the previous section. The part of constructing the allowable limit spectrum will follow these blocks. At first designing the equipment according to the functional requirement and other normal loadings, the stress distribution can be obtained. Then comparing this distribution to the allowable stresses, we can find the stress margin distribution through the equipment against each stress categolies, such as primary stress PL + Pb, secondary stress $(PL + Pb + Q)_E$ and fatigue limit. And these margin establish the allowable external force at each boundaries like nozzles and shear rags of a reactor pressure vessel, supporting legs of a heat exchanger, piping supports and so on. This force margin is expressed by a force vector, which consists of three force and three moment components. Usually it is $(N,Q,M)^T$ as shown in Fig. 3, where N, Q, M are axial force, shear force and bending moment respectively. Number of elements included in the vector depends on the code and practice. Share of the margin to each component can not be established in the definite solution. According to the criteria of the related code, it makes a restriction surface as shown in Fig. 4. This figure is only for illustration, and has no exact meaning. These procedure belong to Section A of Fig. 3.

In Section B, based on DBE and other conditions, modes of failures4) of various points of the equipment should be selected. This process is very important, because there is a possibility to miss one or two of them by designer's error. In some cases design requirement will not only be written by the allowable limit, but also written by the functional allowable limit of deformation and so on. The flow of design in such cases is not much different. Until the procedure of deciding design allowable seismic coefficient K_r , we need no response analysis. Afterwards, if we extend the job to draw the allowable limit spectrum, then dynamic analysis should be performed. This is the explanation of the Sections B and D.

The most difficult problem is how to share the total allowance to each force components. The authors introduce an allowable margin external force or stress surface $((N,Q,M))_S^T$. According to a law of summing up the forces or stresses in different categories, this surface in Fig. 4 can be determined. If we assume the design of a nozzle of a pressure vessel, the main force components concerning with the design are N, Q and M. The point B is on the allowable external force vector surface, EFVS. If the force vector pointed to the point B would show the adequate combination of elements which are obtained by the structural analysis of a vessel and piping system under DBE condition, then it is an optimum solution. However, usually it is difficult to obtain such a solution directly. If a model system is so simple, and only the bending moment component is significant, the vector points to the point A and M_l is the solution. In general, we assume an approximate value of bending moment M_1 . By the structural analysis N_1 and Q_1 can be calculated. If the point C is inside of the EFVS, this design is usable. To cut off the extra margin, some iteration method approaching to the point B from C can be introduced. This is the allowable external force vector, EFV. Then the flow is continuing to decide the allowable seismic coefficient.

2.3 Allowable Seismic Coefficient

After we obtain EFVs at all critical points and for all considerable criteria, the minimum, that is, the severest EFV should be found out. This procedure was described in Section 2.1 using a simple example. Then, by comparing to the result of the structural analysis based on DBE, we can calculate the allowable seismic coefficient K, ASC, of the vessel. As shown in Fig. 3, at first we choose the EFV at the point r for all criteria, and calculate the seismic coefficient K_r at the point r. Then we choose the minimum, most critical one through the vessel as K. Most of cases, this method is more practical. For inline simple elements like valves, we may calculate K by primary stress caused by seismically induced bending moment only. However we should notice that the axial force sometimes brings unexpected local bending stress Pb in its casing. The K_r in Fig. 5 expresses that of the point r, which is the most critical one through the vessel.

3. Allowable Limit Spectrum

The concept of ASC is suitable for a rigid system. If the system has its eigen-frequencies in the region less than 20 or 30 Hz, we should calculate it allowable limit spectrum. As the concept of ALS is already described, it is related to the endurance limit spectrum. The Fig. 5 is again the schematic drawing. Here we assume a ground motion spectrum, the vibration characteristics of the supporting building as f_{b1}, f_{b2}, --- and those of the equipment as f_{e1}, f_{e2}, --- . As shown in the lower half of the figure, floor response spectrum should not exceed the ASC. This concept is the comparison made at the viewpoint of seismic force level of the equipment. If we bring down the reference point to the mounting floor level, then the relation becomes as shown the upper half of the figure. The peak ground acceleration or the peak floor acceleration, defined as α_f , should be compared with ALS. The ALS is the upside-down form of the ordinary response curve of the equipment, so it is easy to draw it except introducing the assumed inputs. In this figure two sorts of ALS are drawn, the chained line is based on the response spectrum to sinusoidal inputs, and the solid line is based on the response spectrum to assumed inputs. To draw the solid line we should assume the ground motion spectrum and the vibration characteristics of the supporting building before the design. This is not along the line of the standardization of the equipment. However, for the alternative mean, the chained line is drawn under a simple assumption like sinusoidal continuous inputs, and does not depend on the assumption we made before. However, sometimes it brings very severe results. Therefore another type of inputs can be introduced also such as n-waves chopped sinusoidal input, beating sinusoidal input, intermittent beating sinusoidal input and so on. If we do not have on exact idea on the building, the ground motion spectrum shows the upper bound value of floor motions through the building.

The simple example of the application to the piping design described in Section 2.1 is taken from the result of stress analysis for primary stress criteria. Such a case is quite similar to that of nozzle part of a pressure vessel. And those of supporting structures, hangers and other supporting devices are also the same. If we combine the idea of ALS with the simplified design method of lower categolized pipings, then some new practical methods can be developed. The authors developed a method5): i) by limiting the maximum length of the piping based on its configuration and size against the limitation of lower bounds of its eigen-frequencies, ii) unless the design criteria i) will be satisfied, then ASC of the piping based on primary stress criteria. If we limit the shape of the piping using standard modulai like L-shape and Z-shape pipings, we can give a band of ASC, K_r , on the floor response curve drawing. Kato made more simplified method, that is, he obtained this band from the fundamental eigen-frequency of a simple fix-fix beam and that of a pin-pin supported beam.

The authors mentioned three levels for the counter-input comparison. Which parts of nuclear power stations is suitable to which method? We can tabulate on the whole items both in PWR type stations and BWR type ones, however, there is no space more. The authors try to pick up some typical examples. As already explained, EFV method is applicable to nozzle parts of vessels. Also to supporting legs or rags of vessels. ASC method is applicable to most of Class B or II items. ALS method is to Class A or I Electrical equipment. Primary coolant system, main steam pipings and other such pipings can be considered to be suitable to ALS method also, however, it is the possibility of raising some difficulty to dispatch the stress components to the margin surface, if they have all six components of forces and moments.

Shibata will discuss the problem of failure rate under earthquake conditions in the paper K2/6. The distance between ALS to the line α_l or the ground response spectrum in Fig. 5 may give the figure of the reliability. As an ordinary criterion, ALS can not lower than such critical line. However, if we think it along the line of failure rate analysis, we can evaluate the value based on its mode of failure and other informations as described in the other paper. Usually, there are various types of margins through the system. On the other hand, the uncertainty of response analysis, brought by the fluctuation of response, reduces the margin. But the partial intersect of these line may be admitted, if such sort of studies will be performed in some extent.

4. Acknowledgement

This study was done for the preliminary stage of the works6) which have been developing by the sub-committee on the standardization of anti-earthquake design of equipment and pipings, the Ministry of International Trade and Industry. The committee is working to establish these method with calculations on many examples on various types equipment and pipings. The authors wish to express their gratitude to the works and discussions by the members of the committee and also the officials of the sponsoring organization.

Fig. 1 was prepared by Mr. M. Shintani for his Master's theses. The manuscript was composed and typed by Miss. F. Ogino. The authors express their gratitude for their works.

/ 1 / Shibata, H., " On Response Analysis for Structural Design and its Reliability ", *Proc. of 3 SMiRT*, K4/3*, (1975).

/ 2 / Shibata, H., and Others, " On the Reliability of Anti-earthquake Design of Structures ", *Reliability Approach in Structural Engineering* (Freudenthal *ed.*), Maruzen, (1975) 115.

/ 3 / Shibata, H., " Proving Test of Earthquake-Resistant Pipings, Equipment and Active Components ", *Nuclear Eng'g. and Design*, Vol. 46, No. 1, (1978) 169.

/ 4 / Shibata, H. and Others, " On Estimated Modes of Failure of Nuclear Power Plants by Potential Earthquakes ", *Nuclear Eng'g. and Design*, Vol. 28, No. 2 (1974) 257.

/ 5 / Japan Electric Assc., " Technical Guidelines for Aseismic Design of Nuclear Power Plants ", (1970) 190 and 216 (in Japanese).

/ 6 / Subcommittee on Aseismic Design, " Report on Standardization of Aseismic Design of Light Water Reactor-1977 ", *Report on Standardization of Light Water Reactor- part 5 -*, Ministry of International Trade and Industry, (1978) (in Japanese).

Table 1 Dispersion Factor $d = \sigma/m$

[%]

Vibration characteristics	Light damped 0.7 %	Moderate 2 %	Highly damped 7 %
Rigid	18	12	12
Resonate	42	32	21
Flexible	50	44	29

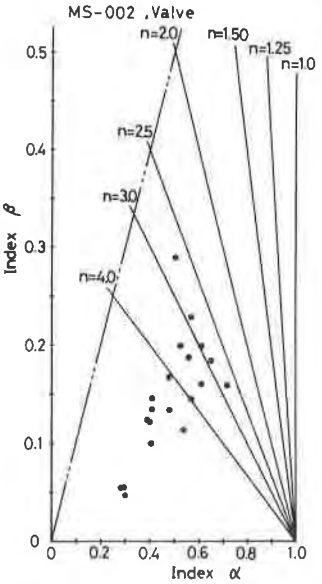

Fig. 1 Rate of Earthquake Induced Stress to Total Stress of A Main Steam Line under DBE Condition

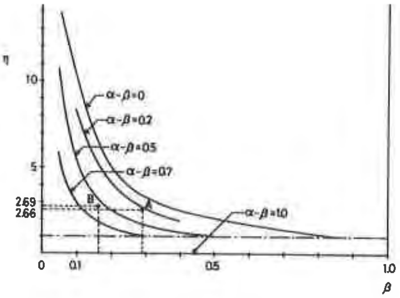

Fig. 2 Factor $\eta = \alpha_{limit} / \alpha_{dbe}$ as a Function of Factors α and β

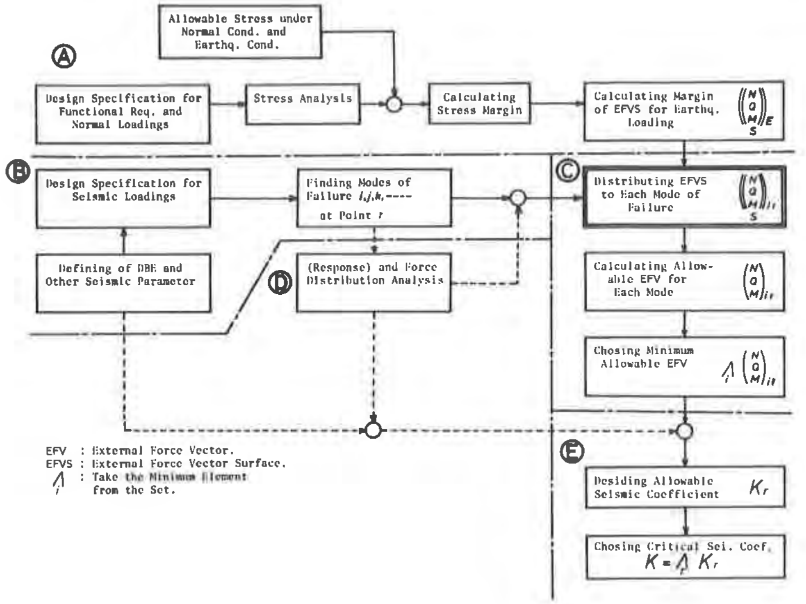

Fig. 3 Flow Chart of " Counter Input Design Method "

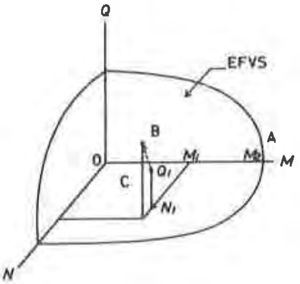

Fig. 4 Concept of Allowable External Force Vector Surface, EFVS

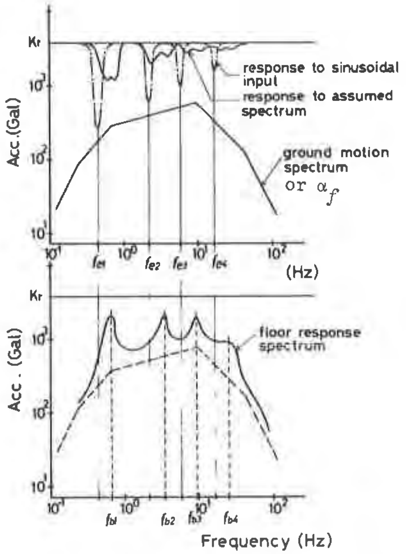

Fig. 5 Schematic Figures on the Relation of Allowable Limit Spectrum to Reference Floor Motion Spectrum