Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Ductility and seismic design criteria

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ABSTRACT : In this paper is presented the classical classification of stresses that holds in nuclear engineering : primary stresses (due to force controlled loadings) that support much more severe design criteria than secondary stresses (due to displacement controlled loadings). A methodology is presented in order to cope with the question of seismic input ; the primary stress ratio τ is introduced. Analysis leads to the conclusion that τ is frequency dependant.

1 INTRODUCTION

This paper deals with some researchs that are carried out in France in the field of non linear responses of structures to earthquake input, focusing on the effect of eigenfrequency and related to regulatory rules.

Most of earthquake engineering applications are in the field of civil engineering, with the aim of prevention against loss in lives due to a bad design of buildings. But it has to be underlined that another potential and important risk for populations is the destruction by an earthquake of particular industrial facilities as some chemical of nuclear plants. The presented research is motivated by safety analysis of Nuclear Power Plants, more precisely by safety analysis of equipments as the primary loop of a pressurized water reactor, or other piping systems. While the equipments are principaly made of steel, a quite simple consecutive law, as presented further, can lead to interesting results. Yet, the authors think that the proposed approach holds for the analysis of structures in general and that profitable conclusions can be derived, even if only qualitative.

The precise field investigated in the present paper is about elastic-perfectly plastic behaviour of a single degree of freedom system. Effects of the frequency-ductility couple are analized. Other researchs taking into account hardening, mutlti-modal structures... are also carried out but are not presented here. Nevertheless, this simplified approach enables to present general ideas and main results.

2 PRIMARY AND SECONDARY STRESSES

2.1 Presentation of stresses classification

Identical straight rods (figure 1) are considered, made of the same material, tensile curve of which is presented on figure 2, and reads : $\sigma = f(\varepsilon)$

Case 1 : The first rod is loaded by an imposed force F_1 ; tensile stress in the rod is :

$$\sigma_1 = F_1/S \quad (1)$$

Case 2 : The second rod is loaded by an imposed displacement D_2 ; tensile strain and tensile stress in the rod are :

$$\varepsilon_2 = D_2/L \ , \ \sigma_2 = f(\varepsilon_2) \quad (2)$$

In case 1, stress level is controlled by equilibrium equation because loading is force-controlled. In case 2, stress level is controlled by tensile curve because loading is displacement-controlled.

Now we assume an elastic behaviour of rods ; we denote $\tilde{\sigma}_1$ and $\tilde{\sigma}_2$ the resulting stresses in the rods. We obtain :

$$\tilde{\sigma}_1 = \sigma_1 \quad (3)$$

$$\tilde{\sigma}_2 = E\varepsilon_2 \ \text{ i.e. } \ \tilde{\sigma}_2 \neq \sigma_2 \quad (4)$$

Practically design analysis of structures is carried out assuming an elastic behaviour, consequences of what are now presented.

2.2 Design criteria

A limit imposed force F_u and a limit impose displacement D_u are corresponding to collapse of rods 1 and 2. A safety factor k is decided so that the maximum admissible force on rod 1 is F_u/k and the maximum admissible displacement on rod 2 is D_u/k.

The question is now the following one : assuming that only elastic analyses are carried out and that stresses are calculated, what are the maximum admissible stresses so that the safety factor k holds ? It is very easy to proof that the answer is (see notations on figure 1) :

$$\tilde{\sigma}_1 \leq \frac{\eta\,\sigma_e}{k} \ \text{ and } \ \tilde{\sigma}_2 \leq \frac{\mu\,\sigma_e}{k} \quad (5 \text{ and } 6)$$

Is ASME code or in French Nuclear code RCC-M $\tilde{\sigma}_1$ is named a "primary stress" and $\tilde{\sigma}_2$ a "secondary stress" ; (5) and (6) are typical corresponding design criteria. It has to be observed that criteria (5) is much more severe than criteria (6) at least in a factor 10.

Of course usual seismic design in nuclear as in non nuclear engineering is founded on elastic behaviour of structures. Consequently a question arises : which type of criteria has to apply ? Or in other words, is the seismic input force-controlled or displacement-controlled ?

The two criteria are so different that the question is a central concern of seismic design. It will be now answered in a simple case.

3 PRIMARY ASPECT OF SEISMIC LOAD

3.1 Dynamical S.D.O.F. system

A third rod (rod 3 of figure 1) is now under consideration identical to the previous ones, but at its free end is added a lumped mass m (the rod itself is supposed massless). So is obtain in tension the model of a dynamical single degree of freedom system (an oscillator). Changing m leads to change eigen-frequency of the system. Furthermore a damping can be assumed in the system.

3.2 Methodology

Rod 3 is submitted to a dynamical load. The proposed methodology applies for all the types of dynamical load ; in the case of a seismic input, loading is described by the acceleration of the support : g(t).

In a first step, g(t) is calibrated so that the yield limit is just reached during the time history response of rod 3 ; the corresponding accelerogram is denoted $g_e(t)$.

In a second step, successive increasing inputs $\lambda g_e(t)$ are applied on the oscillator ($\lambda > 1$) and elastic-plastic analyses are carried out. $\lambda_u g_e(t)$ denotes the ultimate accelerogram for which ultimate state (ε_u, σ_u) of the oscillator is just reached during the corresponding time history. According to §2.1, we can say that :

- if $\lambda_u = \eta$, g(t) is a primary load, or acts as a force-controlled load,
- if $\lambda_u = \mu$, g(t) is a secondary load, or acts are a displacement-controlled load.

3.3 Primary stess ratio

We denote $\tilde{\sigma}_3$ the elastically calculated stress in bar 3 submitted to the dynamic load ; as a consequence of above methodology, we can conclude that collapse occurs in bar 3 for $\tilde{\sigma}_3 = \lambda_u \ \sigma_e$. Then, including k safety factor, design criteria reads :

$$\tilde{\sigma}_3 < \frac{\lambda_u \sigma_e}{k} \qquad (7)$$

In order to obtain a criterion comparable to (5), we rearrange (7) in :

$$\frac{\eta}{\lambda_u} \tilde{\sigma}_3 < \frac{\eta \sigma_e}{k} \qquad (8)$$

Then the criterion is the same as for a primary load ; but on the left hand side a correcting coefficient appears so that the primary stress criterion applies. Consequently this coefficient is named the primary stress ratio ; it is denoted τ :

$$\tau = \frac{\eta}{\lambda_u} \text{ : primary stress ratio} \qquad (9)$$

We can observe that for a perfectly plastic material, we have :

$$\tau = \frac{1}{\lambda_u} \qquad (10)$$

3.4 Results

Proposed methodology was applied on a serie of elastic-perfectly plastic oscillators, frequencies of which are in the range of seismic input.

Several types of seismic input were considered :

- typical ground motion input with a wide band spectrum,
- typical floor motion inputs obtained by filtering the previous one (filters at 5 % damping, typical of buildings).

Figure 3 presents the primary stress ratio τ versus a non dimensional frequency ν defined as follows : ω is the circular frequency of the oscillator ; ω_o is the central circular frequency of the input motion : $\nu = \omega / \omega_o$.

It can be observed that :

- for very low frequency oscillator, $\lambda_u \rightarrow \mu$ i.e. $\tau \rightarrow 1/\mu$) : the seismic input acts as a displacement-controlled load,
- for very high frequency oscillators, $\lambda_u \rightarrow 1$ i.e. $\tau \rightarrow 1$: the seismic input acts as a force-controlled load.

4 COMMENTS AND CONCLUSION

Two types of comments can be made on regulatory rules and on practical considerations on as built structures. Up to now, nuclear regulatory rules as ASME or RCC-M codes require design criteria so that a) the admissible seismic input is in the order of magnitude of $g_e(t)$, and b) the seismic input is regarded as a primary load. Then important margins are obtained in the design of equipments because steel ductility is very large. And lower is the frequency, greater is the margin.

On the contrary, in classical design codes for houses and buildings, seismic input is typically regarded as a displacement controlled load. Theoretically this approach is valid as frequencies of building are quite low (particularly for towers). But it has to be emphasized that margins are only in the gap between the as-built ductility and the assumed ductility in regulatory rules (depending on the seismic code under consideration, an explicit or an implicit ductility is taken into account).

Consequently if the as-built ductility is lower than the "regulatory ductility", catastropic events has to be expected. Dramatic examples of such a situation were observed after major earthquakes.

We also have to be carefull about a wrong interpretation of figure 3 : the presented margins are valid as far as the design is based on yield limit and as far as the assumed ductility holds. It cannot be derived that in any case it is better to build a flexible structure than a stiff one. The practical conclusion can even be the opposit one because another phenomenon is in competition with margins : the more flexible is a structure, the larger is the demand in ductility during an earthquake.

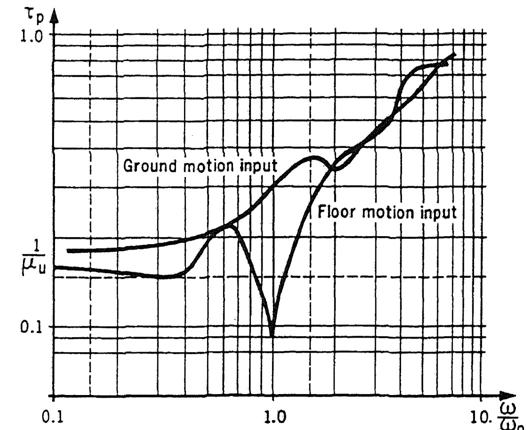

Figure 3 : Primary stress ratio
(On the figure, $\eta = 1, \mu = 6$)

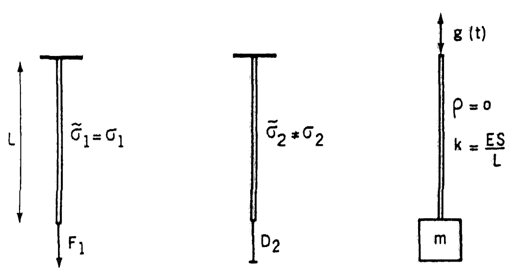

Figure 1 : Stresses classification

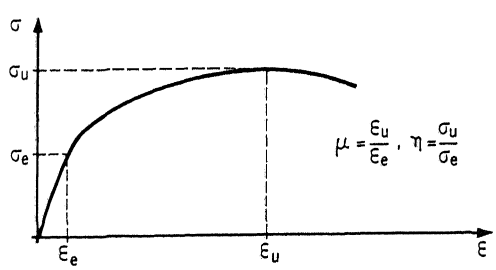

Figure 2 :Tensile curve