Franklin Research Center
A Division of The Franklin Institute

CT-1106
PDR 5/18/79

April 16, 1979

RECEIVED
ADVISORY COMMITTEE ON
REACTOR SAFEGUARDS U.S. N.R.C

APR 18 1979
AM PM
7,8,9,10,11,12,1,2,3,4,5,6

Dr. Paul G. Shewmon
Professor and Chairman of
Metallurgical Engineering Dept.
Ohio State University
Columbus, Ohio

Re: Buckling Criteria for Free Standing Containment Shells of Nuclear Power Plants

Dear Professor Shewmon:

In the enclosure, I have discussed in detail the current situation in evaluating containment adequacy to resist the buckling mode of failure. As indicated, there are no precise criteria available; hence, decisions made during the licensing review process are not necessarily unique or consistently the same from case to case. To resolve this problem NRC should undertake research to:

1) Evaluate existing experimental results to determine actual buckling loads for configuration similar to containment buckling. This is equivalent to determining the factor C_A which indicates by how much the theoretical linear bifurcation buckling load must be reduced to account for deviations from perfect geometry and nonlinearities as they may exist.

2) Encourage (or sponsor) development of shell of revolution computer program with capability to consider the nonsymmetric prebuckling states as well as mutliple Fourier summation for buckling modes.

As indicated by Dr. Hafiz, Item 1 above might be partly resolved in the research sponsored at International Structure Engineers. I have seen a Draft Report, dated October 1978, which presumably does not represent the total output anticipated under this contract.

The comments I made at the Sequoyah Fall Committee meeting on 6 April 1979 are brought into better perspective if one looks at the results in the light of the discussion of the enclosure to this letter.

The applicant presented in the buckling analysis report two sets of results which were claimed to support each other. One set of results was based on linear bifurcation analysis which came up with a buckling load factor $C_B = 4.6$ (CBI analysis). If this result is interpreted in the context of NE-3222.1 (a) (2) discussed in the enclosure, the acceptance criteria would require application of a factor of safety $C_S = 1/3$ and possibly $C_S = 1.2$ for service type.

The criteria then would read

$$C_A C_B C_C C_S \geq 1$$

$$C_A \, (4.6) \left(\frac{1}{3}\right) 1.2 \geq 1$$

$$1.82 \, C_A \geq 1$$

$$C_A \geq 0.54$$

which means that the imperfections and other unaccounted-for effects should not cause the actual structure to buckle at less than a half of the computed load. I believe this is adequate demonstration of the Sequoyah's containment capability to resist gross buckling failure mode.

What I consider inappropriate is the statement in FSAR, page 3.8.2.-3, which essentially says that in lieu of originally defined buckling criteria (which could not be satisfied), the applicant used Anamet Dynamic Analysis. This is an implication that the analysis referred to represents an exact analysis in the spirit of NE-3222.1 (a) (1). If such had been the case, the results by this analysis should have indicated instability at a considerably lower load than that by CBI analysis. Instead, both analyses seemed to have confirmatory results. My concern in this context is that I consider the computer program used for the above analysis not adequately validated to put such a trust in it.

The local panel buckling analysis using STAGS programs came up with $C_B = 2.5$, although it is true that C_A may be close to 1 for this case, the result is uncomfortably close to the limit and it might indicate some additional conservatism in the model not specifically identified.

Very truly yours,

Zenons Zudans/ces

Zenons Zudans
Senior Vice President, Engineering

ces

encls.

cc: Prof. M. Plesset, Cal. Inst. of Technology
Mr. R. Savio, ACRS
Mr. A. Bates, ACRS

APPENDIX

DISCUSSION OF BUCKLING CRITERIA FOR STEEL CONTAINMENT VESSELS

Subsection NE of the ASME Boiler and Pressure Vessel Code, Section III, Division 1 establishes rules for design and certification of metal containment systems.

Subsection NE-3133 of this code provides rules for determining the thickness under external pressure loading in spherical shells and cylindrical shells with or without stiffening rings.

In most practical applications, it turns out that cylindrical containment vessels reinforced only with circumferential rings does not satisfy the buckling criteria of NE-3133. In such cases, the actual containment vessels is provided with meridional stiffeners (stringers) having substantial cross-section in addition to the vessel wall and circumferential rings. There are no criteria for this type of design, neither are there criteria for the design of rather complex configurations with cut-outs, curvature transitions and other detail consistent with functional requirements. Instead of such criteria, NE-3200 allows design by analysis. In particular, NE-3222 describes the buckling stress allowables as quoted below.

NE-3222 BUCKLING STRESS VALUES

NE-3222.1 Basic Compressive Allowable Stress. The maximum buckling stress values to be used for the evaluation of instability shall be either of the following:

(a) One-third the value of critical buckling stress determined by one of the methods given below:

  (1) Rigorous analysis which considers the effects of gross and local buckling, geometric imperfections, nonlinearities, large deformations, and inertial forces (dynamic loads only).

  (2) Classical (linear) analysis reduced by margins which reflect the difference between theoretical and actual load capacities.

  (3) Tests of physical models under conditions of restraint and loading the same as those to which the configuration is expected to be subjected.

(b) The value determined by the applicable rules of NE-3133.

While the intent of NE-3222 appears to be clear the following discussion demonstrates the difficulties the designer faces:

NE-3222.1 (a) (1) sounds nice, but is obviously impractical to apply. First there are no analysis tools which can be generally accepted as "rigorous." Most analyses claimed today as having the "rigorous" characteristics, suffers from symptoms which to say the least make that claim unreal. While purely technically it is possible to define methodology qualifying as rigorous the lack of precise information of imperfections of the containment "as built" preclude this approach anywhere. There have been statistical imperfection definitions used in connection with the reduction of buckling capability calculation. Such efforts, however, are essentially well enough developed for publication of a paper and not for actual design work. In conclusion, I do not believe NE-3222.1 (a) (1) provide guidance, it is subject to misuse by claims of rigorous capability which in reality does not exist.

NE-3222.1 (a) (2) describes a method which has a good chance of unambiguous implementation. To summarize what this paragraph says let's us walk through analysis steps performed to comply with these criteria.

Suppose we have been given a steel containment structure such as that Sequoyah Nuclear Power Plant. With today's existing capability we can compute stresses in such a structure due to all applied heads (such as ice condenser originated nonsymmetric pressures). We call this "prebuckling state of stress" and denote the corresponding load P_L. Linear bifurcation buckling analysis will yield a minimum buckling factor, C_B. This factor, times the applied load, P_L, will yield the minimum linear bifurcation buckling load for a perfect structure

$$P_{bif} = C_B P_L \quad .$$

Paragraph NE-3222.1 (a) (2) requires that this classical linear bifurcation buckling load, P_{bif}, be reduced by a factor, call it C_A, to determine the actual buckling load capacity, P_{crit}, as it may exist for a real structure,

$$P_{crit} = C_A P_{bif} = C_A C_B P_L$$

The value of C_A depends on the geometry and the nature of the imperfections in the real structure as manufactured as well as the material's non-linearities should they occur.

In the next step the allowable buckling load, P_a, is determined by applying a safety factor, C_S, and a service condition factor, C_C, to the critical load,

$$P_a = C_C C_S P_{crit} = C_A C_B C_C C_S P_L$$

The safety factor, C_S, is given as 1/2 by NRC Reg. Guide 1.57, and as 1/3 by NE-3222.1.

NE-3222.2 (1977) gives C_C as 1.0 for normal operating service, 1.2 for emergency service, and 1.5 for faulted condition. By this approach design will be acceptable if the allowable buckling load exceeds the actual load

$$\frac{P_a}{P_L} \geq 1 \quad \text{or} \quad \frac{P_L}{P_a} \leq 1$$

which is equivalent to

$$C_A C_B C_C C_S \geq 1 \text{ or } \frac{1}{C_A C_B C_C C_S} \leq 1$$

where C_A: Factor reducing linear bifurcation load of a perfect structure to actual buckling load of a real structure.

C_B: Factor multiplying applied load to yield linear bifurcation buckling load of a perfect structure.

C_C: Factor correcting the load allowable for the load service condition.

C_S: Factor of safety applied to the critical buckling load of a real structure.

Are there any problems associated with the implementation of the approach based on NE-3222.1 (a) (2)? We answer this question by analyzing various multipliers needed to obtain the allowable buckling load P_a.

1) C_B - factor yielding linear bifurcation load with P_L being the prebuckling load. When shell of revolution analysis methodology is used in currently popular form there may be some question as to the accuracy with which C_B can be computed. This arises from the fact that applied loadings are not axisymmetric (such as compartment pressures for the ice condensor containment building, SRV discharge lead in MARK III BWR and seismic loads in all LWR's). Shell of revolution based computer programs would produce nonsymmetric prebuckling state. However most such computer programs cannot use the nonsymmetric prebuckling state as the basis for bifurcation buckling analysis. This is due to the fact that for non-symmetric prebuckling load pattern the major advantage of shell of revolution approach is lost: the Fourier expansions of leads and responses no longer uncouple and one is forced

to analyze *all* harmonics simultaneously. Commonly used approach is to select the highest compressive stressed meridian and use it as an axisymmetric prebuckling state. It is then claimed that the C_B thus computed is conservative, an assertion intuitively plausible, but yet to be proven for *all* structures to which it is applied. If one considers non-symmetric prebuckling load say such that only one quarter of the shell is under compression in meridional direction it is not unreasonable to postulate that the governing mode of buckling may not be periodic in circumferential direction as it will result with axisymmetric prebuckling state, but may consist of a number of Fourier terms acting simultaneously such that only the vicinity of compressive regions will determine the buckling mode. All shell of revolution computer programs used today look at buckling modes in the form of Fourier terms one by one and select the Fourier term producing smallest C_B as the bifurcation buckling mode. The obvious result is that the computer buckling mode circumferentially is of a single Fourier term type. This situation can be resolved by developing a shell of revolution program capable of using non-symmetric prebuckling state and also examining C_B for various combinations of several Fourier terms. Alternative way of accomplishing the same objective is to use currently existing surface type (two dimensional) finite element programs to compute C_B. If one is able to cope with the resulting economic penalty this approach can be used. Additional refinements in the form of refined local modelling can be used to improve the resolution and the economics.

2) C_A - factor reducing linear bifurcation load to that of real structure. This factor, C_A, represents the major unknown in connection with the methodology of NE-3222.1 (a) (2). The only way credible C_A can be produced is by comparing analytical results to actual test results. Significant amount of testing already has been done which would allow to determine C_A with fair degree of confidence for a number of configurations. What is needed is a systematic and comprehensive review of all available data and comparison of these to linear bifurcation analysis to define C_B with an acceptable level of confidence. To quote but a few NASA SP-8007, [1]*, NASA CR-912, [2], represent a significant contribution in this direction. Similarly a recent paper by Miller [3] provides a comprehensive study on

---

*Number in brackets, please refer to list of references.

axially compressed cylinders most recently final draft report "Buckling Criteria Application of Criteria to Design of Steel Containment Shell" [4] attempts to address this subject in greater detail.*

At the time of this report I have not studied the conclusions of the above report in detail. Based on oral information conveyed to me by Dr. Hafiz it appears that authors of [4] have come up conclusions similar to those expressed here.

3) C_C,C_S - There is no difficulty in assigning appropriate values for these factors.

NE-3222.1 (a) (3) allows experimental method to be used to determine the buckling load. I believe this is totally impractical for two reasons: a) can not test full scale containment building, b) there is no way to model containment building to represent it realistically.

In conclusion it is my opinion that a method similar to that described here under NE-3222.1 (a) (2) should be considered as the basis for buckling criteria of containment buildings. Research should be conducted to determine C_A for typical structures and loads. Factors C_B can be determined by finite element (2-D) methodology. Improve shell of revolution analysis should be made as discussed under 1) C_B above.

REFERENCES

1. NASA SP-8007 Buckling of Thin-Walled Circular Cylinders, Sept. 1965, Rev. August 1968.

2. NASA CR-912, Shell Analysis Manual, by E. H. Baker, A. P. Cappelli, L. Kovalevsky, F. L. Rish, and R. M. Verette, prepared by North American Aviation, Inc., April 1968.

3. C. D. Miller "Buckling of Axially Compressed Cylinders," ASCE, Journal of the Structural Division, ST3, pp. 698-721, March 1977.

4. Buckling Criteria and Application of Criteria to Design of Steel Containment Shell, International Structural Engineers, Glendale, CA 91206, October 1978, prepared for Structural Engineering Branch, Division of Systems Safety, U.S.N.R.C., under Contract NRC-03-77-131.

---

*Dr. A. Hafiz, USNRC technical monitor.