Thermal Ratcheting and Progressive Buckling

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ABSTRACT

Pure elastic buckling is not a frequent mode of failure and plastic deformations often occurs before buckling - like instability does. Elastic-plastic buckling is very difficult to analyse. The most important difficulty is the material modeling. In the elastic plastic buckling phenomena, small modifications of the material constitutive equation used are of great influence on the final result.

When buckling cannot occurs, it is well known that distorsion due to applied loads is greatly amplified when there is also some cyclic straining (like thermal stresses). This effect is called ratcheting — and thermal ratcheting when caused by cyclic thermal transients. As cyclic thermal stresses can be applied in addition of load able to cause buckling failure of a component, the question arise of the effet of cyclic thermal stresses on the critical buckling load. The aim of the work presented here is to answer that question : "Is the critical buckling load reduced when cyclic straining is added ?".

It seems sensible to avoid premature computation based only on arbitrary assumptions and to prefer obtaining a sound experimental basis for analysis. Sufficient experimental knowledge is needed in order to check the validity of the material modeling (and imperfections) used in analysis.

Experimental tests on buckling of compressed columns subjected to cyclic straining have been performed. These experiments are described and results are given.

The most important result is cyclic straining reduces the critical buckling load. It appears that distorsion can be increasing progressively during cyclic straining and that buckling can happen at last at compressive loads too small to cause buckling in the absence of cyclic straining. As progressive distorsion seems to be the process leading to instability, this new type of buckling may be called "progressive buckling".

Comparative analysis is then done with analysis methods of conventional ratcheting. It seems that some connection can be established.

1. The Structures of Pool-type Breeder Reactors are Relatively Thin. Their Resistance to Buckling Must Be Given Careful Consideration. These Structures Are Subjected to Heavy Thermal Transients. Do such Transients Affect the Tendancy to Buckling ?

Pool-type breeder reactors include large components (e.g. vessel, baffles, etc.). Permanent loadings applied to these components are low (weight, pressure) so they can be of thin-wall design. Since the ratio of wall thickness to main dimensions is small (of the order of 1/1000), a careful analysis of buckling conditions is required. It should be emphasized that buckling-type occurrences are nearly always preceded by plastic deformation of the material.

Buckling analysis in the elastic-plastic range is a difficult subject. A substantial development program covering this area is in progress at CEA [1], [2] . Geometrical defects due to fabricating tolerances are highly significant ; material behaviour also plays an essential part. It seems that small changes in the material constitutive equation may significantly alter calculation results. One well-known consequence of this problem is the famous "flow theory versus deformation theory paradox".

It therefore appears necessary to validate analytical methods by an adequate number of tests on structure models.

Although permanent loading is, as stated above, rather low, breeder type reactors are also subjected to heavy thermal transients which cause cyclic deformations of the structures. It is well-known that, in cases where buckling is not to be feared, this type of loading may ruin the structure through thermal ratcheting. The purpose of this paper is to determine whether the same process may occur when buckling is a possibility.

2. In Cases where Buckling is not to be Feared, Thermal Transients Add to the Effect of Applied Loads. A Practical Method Exists to Assess this Additional Loading.

A very extensive program covering thermal ratcheting is in progress at the Saclay Nuclear Research Center. Results have been given in a number of publications [3], [4], [5], [6], [7], [8]. An early establishment was the wide discrepancies which existed between experimental and computed data. This is attributed to over-simplified mathematical modelling of material behaviour.

In addition to the experimental work done at Saclay, published experimental data were thoroughly reviewed. This yielded a practical method for estimating the effect of thermal ratcheting. The method is based on the observation that thermal transients amplify the effects (e.g. deformation) of weight and pressure loads.

The effect of loading due to applied forces such as weight or pressure is characterized by stress P known as the primary stress. Thermal transients are structurally characterized by a variation of thermal stress Q_R (also named "secondary stress"). It should be noted that secondary stresses are not actual stresses ; they are fictitious stresses which would exist if the material were elastic. In fact, Q_R simply represents cyclic strain (e.g., in the tension/compression mode, Q_R is the product of the strain range by Young's modulus).

The presence of Q_R (thermal transients) amplifies the effect of P (weight or pressure). This is equivalent to the structure being subjected to an effective primary stress $P_{eff} = P/V$ where factor V is less than 1. A default value of V can be found as a function of $SQ = Q_R/P$, using the efficiency diagram (Fig. 1) resulting from experimental data.

3. In Cases where Buckling May Occur, the Technical Literature Shows no Indication that Instability Loading May be Reduced as a Result of Thermal Transients. To Obtain Data on this Subject, an Experimental Program Covering Progressive Buckling has been Initiated.

Thus, the cyclic thermal stresses due to thermal transients may cause the ruin of structure through instability at load values which are lower than those prevailing in the absence of such transients. It is conceivable that the effect of these transients would be the same in cases where buckling is a possibility. In other words, the critical buckling load may be lowered in the case of cyclic strain (secondary cyclic stresses) due to thermal transients. For example, initial geometrical defects may be amplified at every transient, finally becoming large enough to cause instability under the applied load. Such a process might be called "progressive buckling".

To date, a review of literature covering buckling has not succeeded in locating a document which might clarify the matter. It is also desirable to validate computations, and one may anticipate significant discrepancies between computed results and actual behaviour. It was therefore decided to undertake an experimental program comparable to that devoted to thermal ratcheting in the absence of a buckling possibility. As a matter of principle, it has been accepted that the configurations used would be similar to those of the thermal ratcheting program. As can be expected, the progressive buckling program, having been initiated at a later date, has not yet produced a large number of data. The purpose of this paper is to present the data and to show how they compare with the thermal ratcheting data.

4. Description of Experimental Set-up and Test Specimens

Thin-walled tubes made of 316 L stainless steel have been subjected simultaneously to :

- static compressive loading
- cyclic torsion strain with set angle Θ.

Both ends of specimen tubes are welded onto solid end-pieces which fit into a special device (see Fig. 2) for applying cyclic torsional motion. The entire unit is mounted in a closed-loop testing machine and a constant compressive load is applied by the machine actuator.

During the test, the following were recorded continuously :

- ΔL, the change in specimen length
- torque
- Θ, the total angle of cyclic torsion.

Tests have been performed at ambient temperature. All specimens had the same initial length Lo = 500 mm. Three tube sizes were tested :

29 mm I.D. × 30 mm O.D.
15 mm I.D. × 16 mm O.D.
10 mm I.D. × 11 mm O.D.

Respective slenderness ratios are 24, 46 and 67.

The mechanical properties of the various tubes used to prepare the specimens were measured ; tubes were used "as received". Yield stress was from 245 MPa to 330 MPa.

5. Available Results

5.1 Specimen Loading should first be Described Clearly

- The primary compressive stress is :

$$P = \frac{\text{Compressive force } F}{\text{Specimen cross-sectional area } A}$$

- Secondary stress Q_R results from the torsional strain range $\Delta\gamma$ applied to the tube :

$$\Delta \gamma = \frac{r\,\theta}{L}$$

where r = outside radius

L = length

Θ = total torsion angle

Based on TRESCA's criterion, the secondary stress intensity is :

$$Q_R = 2\,G\Delta\gamma$$

where G is the shear modulus.

5.2 The first testing phase consisted of measuring critical buckling stress P_{cr} for the three tube sizes. This is the maximum stress measured at instability, under a compressive load with monotonic growth.

Values are given in Table I, which also shows values of P_{cr} in relation to the EULER critical stress and to yield stress $\sigma_{y\ 0.2}$. The value of $\sigma_{y\ 0.2}$ used in this last calculation for individual specimens is the value measured on the tube stock from which the specimen was cut.

The same applies further to standardization of primary and secondary stresses P and Q_R relative to $\sigma_{y\ 0.2}$.

5.3 The effect of cyclic strain added to a constant compressive stress was then determined in the three specimen types. In all tests, primary stress P was limited to approximately 0.6 to 0.7 times the value of P_{cr}.

Test loadings and results are given in Table II.

6. Progressive Buckling May Occur. Thermal Cycling (Forced Deformation) May Lower the Critical Buckling Load. Early Results are not in Contradiction with the Practical Method of Section 2.

These results, which had previously been published, in partial form, in [9], show that progressive buckling may indeed occur. In many cases, column length decreases during the strain cycles ; see Figure 3.

This may be due to the growth of geometrical defects. Ruin through instability occurs following a number of cycles at a load value which is lower than the critical buckling load with no cyclic strain. It is noteworthy that, for a given geometry, the shortening observed when instability occurs is almost the same in all load cases.

For each individual geometry, the critical instability load has been determined experimentally with or without cyclic strain. It is thus possible to assess the amplifying effect of cyclic strain. It is obviously the ratio of uncycled stress P_{eff} (effective stress, equal to P_{CR}) to critical stress P with cyclic strain. It is more convenient to use the reciprocal of this ratio, i.e. :

$$V = \frac{P}{P_{eff}} = \frac{\text{critical stress, cycled}}{\text{critical stress, uncycled}}$$

This value has been plotted on the efficiency diagram (see Fig. 4) against the secondary quotient defined as :

$$SQ = \frac{Q_R}{P} = \frac{\text{variation of secondary stress}}{\text{primary stress}}$$

The secondary stress is the fictitious stress associated with an elastic material subjected to cyclic strain ; it is generally a theoretical stress.

Results obtained to date seem to be in fair agreement with the thermal ratcheting rule.

7. Conclusion

The tests performed to data have shown the possibility of structural collapse through progressive buckling.

There is hope that a preventive rule can be established, as in the case of thermal ratcheting. This will require the continuation of experimental work in this field.

References

[1] HOFFMANN, A., ROCHE, R., JEANPIERRE, F., GOLDSTEIN, S., "Flambement Elastique et Plastique des Coques. Réalisation dans le Système CEASEMT. Résultats Disponibles. Comparaison à des Essais", in French, Revue Française de Mécanique, N°62-63 (1977).

[2] MEZIERE, A., SON, N.Q., et al., "Post Buckling of Axisymmetric α 3D Shells", 6th Int. Conf. on Structural Mechanics in Reactor Technology, Paper M11/1, Paris, France, August 17-21, 1981.

[3] LEBEY, J., ROCHE, R., "Tests on Mechanical Behaviour of 304 L Stainless Steel under Constant Stress Associated with Cyclic Strain", Fatigue of Engineering Materials and Structures, 1, 307-318 (1979).

[4] COUSSERAN, P., LEBEY, J., MOULIN, D., ROCBE, R., CLEMENT, G., "Ratcheting. Experimental Tests and Practical Method of Analysis", Int. Conf. on Eng. Aspects of Creep, 2, Univ. of Sheffield, England, 15-19 September 1980.

[5] LEBEY, J., ROCHE, R.L., "Experimental Tests on Ratchet of Structural Elements. Diagrams for Primary Tension and Secondary Twist", 4th Int. Conf. on Pressure Vessel Techn., 2, London, England, 19-23 May 1980.

[6] COUSSERAN, P., CLEMENT, G., LEBEY, J., ROCHE, R.L., "Simplified Design Rule for Ratcheting Analysis", A.S.M.E. Pressure Vessels and Piping Conf., 60, Orlando, Florida, 1982.

[7] ROCHE, R.L., MOULIN, D., LEBEY, J., "Practical Analysis of Ratcheting", Nuclear Eng. and Design, 71, 51-66 (1982).

[8] CLEMENT, G., et al., "Règles de Dimensionnement des Structures Mécaniques des Réacteurs. Dommage dû aux Chargements Variables. Déformation Progressive. Analyse Pratique de l'Effet de Rochet", in French, Rapport CEA-R-5178 (1982).

[9] BROUARD, D., et al., "Progressive Buckling Caused by Cyclic Straining", 6th Int. Conf. on Structural Mechanics in Reactor Technology, Paper L15/4, Paris, France, August 17-21, 1981.

TABLE I - Results of static compressive tests

Tube size (mm)	Specimen	Slenderness ratio	P_{cr} (MPa)	σ_{Euler} (MPa)	$\frac{P_{cr}}{\sigma_{Euler}}$	$\frac{P_{cr}}{\sigma_{y\ 0.2}}$
29 x 30	A_1	24	264.4	3 340	0.079	1.06
	A_2		269		0.081	1.08
15 x 16	A_1	46	291.6	910	0.32	0.93
	A_2		299		0.33	0.95
10 x 11	I A	67	233.7	428	0.54	0.80
	I B		221.2		0.52	0.75

TABLE II - Tests with primary constant stress and secondary cyclic stress.

Tube size (mm)	Specimen	$P/\sigma_{y\ 0.2}$	$Q_R/\sigma_{y\ 0.2}$	Q_R/P	N cycles	Buckling
29 x 30	A_4	0.65	3.16	4.86	9 844	Yes
	A_5	0.77	3.16	4.10	5	Yes
	B_4	0.65	2.94	4.52	234	Yes
	B_5	0.78	4.11	5.27	3	Yes
	C_2	0.73	4.67	6.40	10	Yes
	C_4	0.73	2.34	3.21	31 290	No
	C_5	0.68	4	5.88	169	Yes
	D_2	0.72	2.94	4.08	4 100	Yes
15 x 16	C_2	0.50	1.27	2.54	4 914	No
	C_3	0.64	2.54	3.97	0.75	Yes
	C_4	0.70	1.27	1.81	1.75	Yes
	C_5	0.64	1.27	1.98	5 980	Yes
	D_1	0.67	2.14	3.19	1	Yes
	D_3	0.51	1.87	3.67	11 000	No
10 x 11	II E	0.55	1.37	2.49	93	Yes
	III B	0.45	1.37	3.04	6 400	No
	III C	0.45	2.35	5.22	2	Yes
	III D	0.45	1.76	3.91	4.25	Yes
	III E	0.45	1.57	3.49	5 750	No
	IV A	0.55	1.57	2.85	0.75	Yes
	IV B	0.45	1.76	3.91	4.75	Yes
	IV.D	0.55	1.18	2.15	5 892	Yes

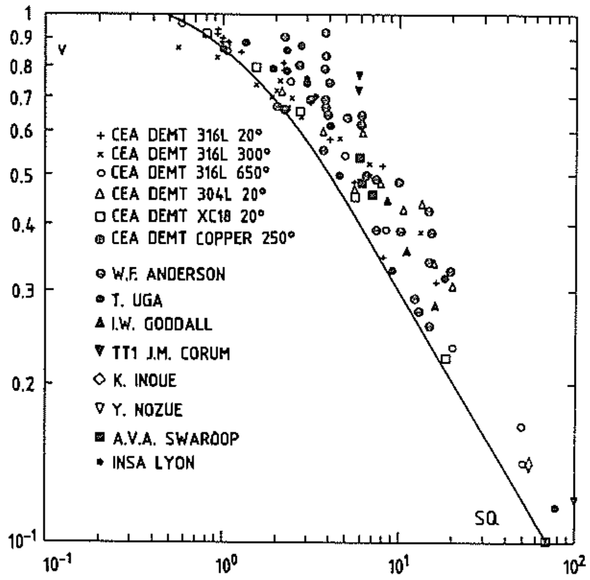
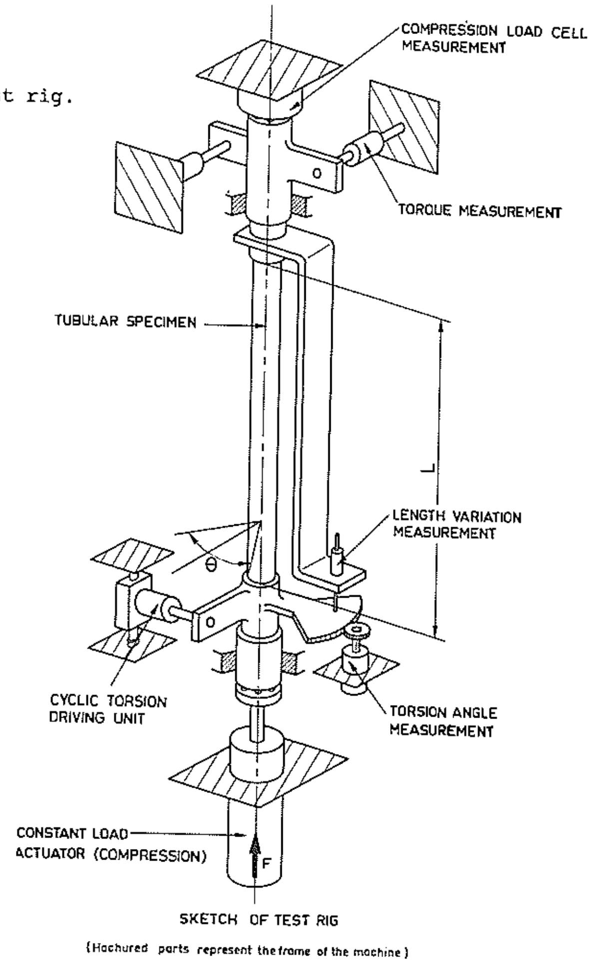


Fig. 1 - Efficiency diagram for thermal ratcheting.

Fig. 2 - Sketch of progressive buckling test rig.



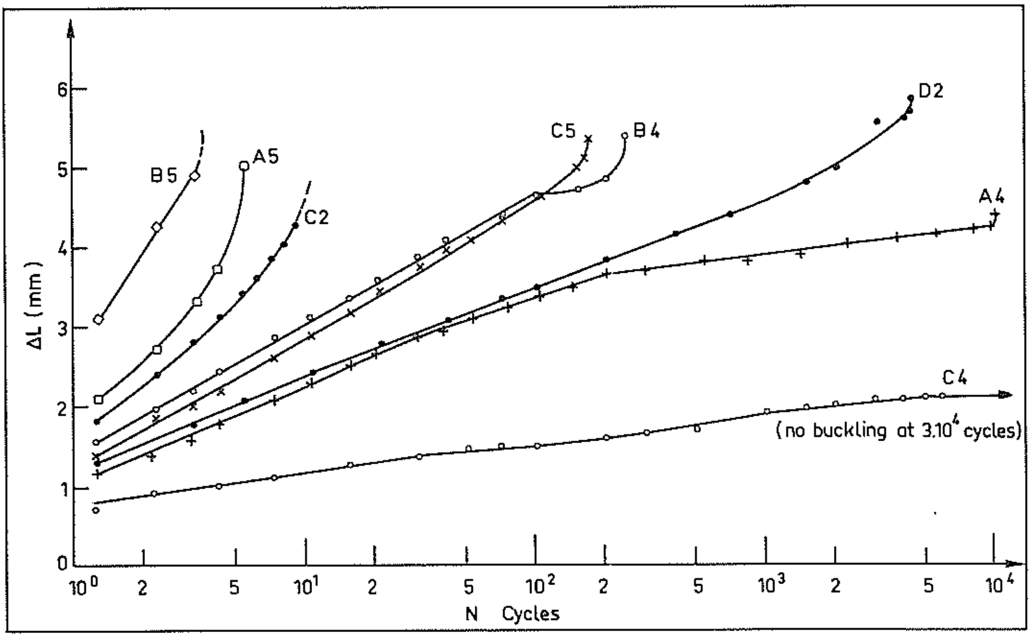


Fig. 3 - Progressive shortening due to cyclic straining.

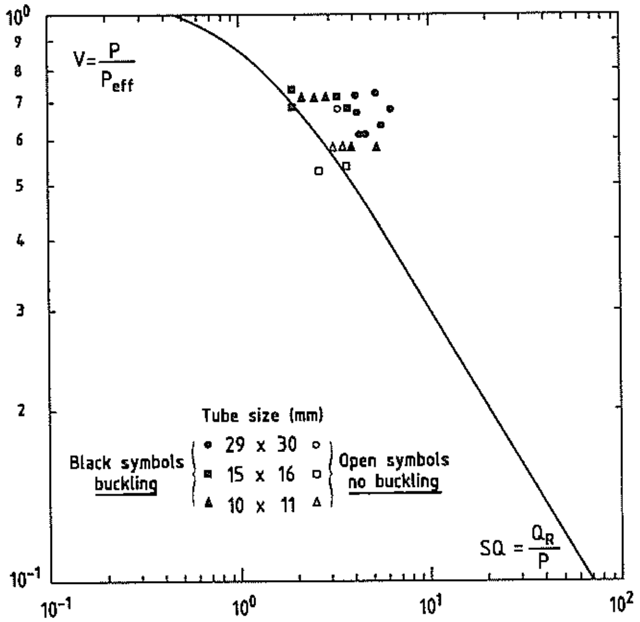


Fig. 4 - Report of progressive buckling data on efficiency diagram.