TRANSACTIONS
of the
7th International Conference on

STRUCTURAL MECHANICS IN REACTOR TECHNOLOGY

Marriott Hotel
Chicago, Illinois, U.S.A. ■ August 22-26, 1983

Vol. L. Materials Modelling and Inelas
Behavior of Materials and
Structures

Conference organization by:

International Association for Structural Mechanics in Reactor Technology

CEC The Commission of the European Communities

ANL The Argonne National Laboratory

Progressive Plastic Deformation in Metallic Liner of Concrete Structure

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SUMMARY

In this paper is described the analysis performed to study the trend of the plastic strains in a liner anchored to the concrete of the biological shield by anchor studs which is subjected to a significant number of thermal load cycles.
Owing to the cyclic thermal loads acting on a liner, this can experience large plastic deformations and their progressive growth because compression loads can cause some panel of liner buckles. Such effect is amplified by possible planarity errors or whatever geometric discontinuities. The cyclic variation of the thermal load causes also a change of the used anchor studs shear characteristic, which is dependent on the stud's materials, concrete properties and liner thickness.
In this context it is necessary to demonstrate that, during the plant life, the maximum liner deformation can satisfy its suitable limits (ad hoc defined) and that failure values of the studs deformation are not reached.
As the assumed reference code (ASME III, Division 2, Subsection CC-3700 - Liner Design) does not provide a complete approach, it has been followed the criterion to show the structure shakes down after a not large number of cycles. The procedure followed to show this, is based on the main following steps:

(1) An experimental way, by means of that it is possible to know the history of the anchor studs shear stiffness versus time.
(2) An analytical phase, by means of that the two following characteristics are defined:
    (a) Load-displacement characteristic for the studs delimitating the buckled panel.
    (b) Load-displacement characteristic of the ends of a buckled panel.
    On the basis of these curves the displacements of the studs and the strains in the liner are determined.
(3) Starting from above results it is possible:
    (a) To evaluate the development of the liner plastic strain state accounting the contemporaneous change of the stud's shear characteristic.
    (b) To determine the load condition that makes sure the shake-down.
    Such a study has been developed and successfully applied to the design of the biological shield's liner of the Italian Nuclear Plant CIRENE.

The design of a liner anchored to a concrete structure must to take into account the following two main items:

a) the stress and/or strain in the liner,
b) the displacements of the anchor points.

Owing to the type of constraints of the liner (for example, circumferential expansion restrained with respect to the concrete), it normally undergoes a compression state by the so-called effective over-temperature, ($\Delta T_{EFF}(+)$). Therefore, we must consider that some row of panels (a panel is the liner region delimitated by four contiguous anchorages) can buckle (this situation may be amplified by possible errors of fabrication or construction of the liner, such as: planarity errors, misalignements, etc.).

In such a case the liner experiences inelastic strains. These strains can grow and progress versus the time owing to:

a) the cyclic variation of the thermal loads (compression due to the effective over-temperature and stretching due to the effective under-temperature),
b) the amount of the planarity error considered (or whatever similar geometric discontinuity),
c) the progressive change in the characteristic curve (load vs. displacement) of the anchors also due to the cyclic variation of the thermal loads. This can be significant, for example, in the case of anchor studs.

Therefore, to perform a reliable structural analysis of the component, it is necessary to evaluate and to determine:

1) the maximum displacement of the anchors,
2) the maximum range of thermal loads oscillation which makes possible that the strains of the liner can stop without exceeding the suitable limits, i.e. what is the range corresponding to the shake-down to the elastic behaviour of the structure,
3) finally, the maximum value of the liner plastic strain in the life of the plant.

The method described in this paper outlines a procedure to evaluate the above parameters and to carry out the structural verification on the basis of ASME III code approach [1]. In addition, because this code does not cover exhaustively such a problem (it does not set limits for inelastic strains and cyclic deformations - see, subarticle CC-3760 "Fatigue"), suitable limits for the liner strains are defined.

This method is based on experimental approach to evaluate the anchor characteristic.

It has been applied to perform the design of the liner for the biological shield of CIRENE reactor. CIRENE is a pressure tube, heavy water moderated, boiling light water cooled, natural uranium fuelled reactor (Figure 1), now under advanced stage of construction. The liner of the biological shield (particular 1 in Figure 1) is anchored to the concrete by means of anchor studs. It seals the concrete for the light water flowing in the cavity around the calandria.

2. Description of the loads acting on the structure.

Generally a liner experiences the following loads:

a) loads due to the differences in temperature between liner and concrete,
b) loads due to the concrete shrinkage,
c) the weight of the structure itself and/or its appurtenances,
d) loads due to earthquake (O.B.E. and S.S.E.).

Among all these loads, the most significant are only the first two types. Both these types of loads are equivalent to a variation of temperature of the liner (with respect to the reference zero stress temperature), while the concrete is at constant temperature. Effective over - and under - temperatures ($\Delta T_{EFF}(+)$ or $\Delta T_{EFF}(-)$) are convenient parameters to evaluate this effect.

The effective over - (or under) temperature is expressed by the following equation:

$$\Delta T_{EFF} = \Delta T^{s}_{EQ.LINER} + \Delta T^{a}_{EQ.LINER} + \Delta T^{o}_{EQ.LINER} \qquad (1)$$

where:

- $\Delta T^{s}_{EQ.LINER}$: accounts the concrete shrinkage effect on the liner with respect to the assembling conditions ($\Delta T^{s}_{EQ.LINER} = \varepsilon_{CONCRETE}/\alpha_{LINER}$),

$\Delta T^{a}_{EQ.LINER}$: ... the difference in temperature and in expansion coefficient between liner and concrete during the assembly ($\Delta T^{a}_{EQ.LINER} = T_{assembly} \cdot (\alpha_{concrete} / \alpha_{LINER} - 1)$),

$\Delta T^{o}_{EQ.LINER}$: similar to $\Delta T^{a}_{EQ.LINER}$, but related to operational phases ($\Delta T^{o}_{EQ.LINER} = T_{LINER} - (\alpha_{CONCRETE}/\alpha_{LINER}) \cdot T_{CONCRETE}$).

The numerical value of ΔT_{EFF} is essentially controlled by the term $\Delta T^{o}_{EQ.LINER}$ so that, depending on the thermal transient in the structure, the quantity ΔT_{EFF} may be negative or positive.

3. General approach.

In the adopted structure model a liner anchored with anchor studs is considered. The structure model has been constructed on the basis of the following assumptions [2]:

a) the liner is assimilated to an infinite plate having the anchorage points on a square grid disposal (see, figure 2);
b) the buckling involves an infinite row of panels (see, dropped zone on figure 2);
c) the buckled zone of the liner reacts with a load which depends on the amount of the displacement of the studs which delimitate this zone and the amount of some defined initial imperfections (as planarity errors, etc.).

Utilizing the above assumptions, two mechanical schemes has been conceived. The first scheme (see figure 3) allows to evaluate the displacement of the studs which delimitate the buckled zone as a function of the reaction load of this same zone. The second scheme (see figure 4) allows to determine the displacement of the extremities of the array of buckled panels as a function of the applied load. It must be noted that such a load (P, in figure 3 or 4) is a compressive one when the load condition is $\Delta T_{EFF}(+)$, and a stretching one when the load condition is $\Delta T_{EFF}(-)$.

To perform the first evaluation, the shear behaviour of anchor studs must be known. This behaviour is determined by experiments as shown in the following chapter.

The two characteristic curves above defined must be calculated by the procedure that will be outlined in the chapter 5. A pair of characteristic curves will be obtained for every load condition.

Finally, drawing on a cartesian plane (having loads as abscissas and displacements as ordinates) these curves, the displacement of the studs which delimitate the buckled region may be determined. It is given by the intersection point of the two above curves, for the considered load condition. Being also known, in such a manner, the displacement of the extremities of the buckled strip of liner, the maximum strain experienced by this zone may be determined.

In figure 5, an example of a pair of the curves above defined corresponding to a load condition $\Delta T_{EFF}(+)$ is shown.

4. Experimental shear behaviour of anchor studs.

The true shear behaviour of anchor studs should be evaluated by means of suitable tests. In fact, the shear behaviour depends strongly on the concrete strength and on the type of the applied load, i.e. if steady or cyclic load. In the latter case, the cyclic repetition of the load, from zero to its maximum value, causes a progressive decrease of the shear stiffness of the anchorage studs. This stiffness generally can stop its decrease and maintain a constant slope after a certain number of repetition, afterwards unchanging it up to rupture.

Such "load-unload" shear behaviour of the anchor studs is ascribing to the deterioration and settlement of the concrete.

In the figures 6,7 and 8 some curves obtained by the experimental program developed in the context of CIRENE plant design are shown.

In figure 6 a comparison among some static experimental shear characteristics (dropped lines) and the static shear characteristic supplied by the manufacturer (continuous line) is shown. Generally a good adherence between these two types of characteristics is noted.

In figure 7 an example of the history versus time of the anchor studs shear stiffness is shown, the studs being undergone to a certain number of cyclic oscillation of the load from zero to the 50% of their rupture value. An initial large variation of this stiffness and a final stop of this variation after 12 cycles are noted.

In figure 8 three curves which envelope the results obtained for many studs and for different percentages of the rupture load are shown. Starting from these curves, it is finally possible to draw a general curve such as that shown in figure 9. This latter curve represents a conservative extrapolation of the final shear stiffness of the studs after a certain number of "load-unload" cycles. Such curve is used to define the end of life shear characteristic of the anchor studs. It has to be used in the method described in this paper.

The above curvescan be represented by an exponential curve such as:

$$T=cx^{\beta} \quad . \qquad (2)$$

5. Determination of the characteristic curves.

In this chapter the method used to obtain the characteristic curves defined in chapter 3 will be described.

5.1. Load vs. deflection characteristic of the rows of studs which delimitate the array of buckled panels of liner.

As above said, the mechanical scheme shown in figure 3 is used to perform the calculation of such characteristic.

The forces acting on the studs which delimitate the buckled region (number 1 row, in figure 3) are the following:

(1) a force T, due to the thermal expansion of the entire liner portion considered;

(2) a force P, due to the reaction of the buckled zone.

These forces are reacted by:

(a) a spring force F(Kp), due to the stiffness of the regions of liner contiguous to the considered stud;

(b) a spring force $F_{i,s}$, due to the shear stiffness of the same considered stud.

The latter forces act on every stud, while the first two forces act only on the studs which delimitate the buckled zone.

The following equilibrium equations can be written:

1) about the studs lying on the first row:

$$T - P - F_{1,p} - F_{1,s} = 0 \qquad (3)$$

2) about the studs lying on the other rows:

$$F_{i-1,p} - F_{i,p} - F_{i,s} = 0, \qquad \text{with } i=2,n \,. \qquad (4)$$

These quantities are defined as follows (with reference to a unit depth):

(a) thermal load T: $T=E\alpha\, t\Delta T/(1-\nu)$ $\quad (N.mm^{-1})$ $\quad$ (5)

(b) spring force of the i-th panel:

$$F_{i,p}=K_p(x_i-x_{i+1}) \qquad (N.mm^{-1}) \qquad (6)$$

where:

$$Kp=Et/(1-\nu^2)d \qquad (N.mm^{-1}/mm) \qquad (7)$$

(c) spring force of the studs lying on the i-th row:

$$F_{i,s} = c\, x_i^{\beta}/d \qquad (N.mm^{-1}). \qquad (8)$$

The equations (3) and (4) form a set of n parametric and non-linear equations, where x_1, x_2, ...x_n are the unknowns and P is the variable parameter. This set is solved by determination of a vector $\{x_i\}$ of n terms for any assigned value of P. The solution of this set of equations is found with iterative procedure. The coefficients of the vector $\{x_i\}$ solving the problem must satisfy the following conditions:

$$x_i^{(nT)} > x_{i+1}^{(nT)}$$

$$x_{i+1}^{(nT)} > 0 \quad . \qquad (9)$$

Being (nT) the n-th iteration whose execution has been necessary because the following other condition is satisfied:

$$x_1^{(nT+1)} - x_1^{(nT)} < \varepsilon \,, \qquad (10)$$

with $\varepsilon \rightarrow 0$.

Since the equation (5) contains the informations about the load condition and the equations (8) contain the informations about the studs shear stiffness (initial and at end of life), two curves can be obtained for any load condition, each corresponding to the proper shear stiffness of the studs.

In figure 10 two families of such curves, obtained for the CIRENE plant, are shown.

5.2. Load vs. deflection characteristic of the extremities of a buckled strip of liner.

This characteristic is determined, as already said, on the basis of the mechanical scheme shown in Figure 4.

An elastic-plastic calculation is performed for an indefinite strip of liner panels, assuming that this strip withstands a compression load P and has its extremities both clamped. An initial planarity error and an initial sinusoidal shape are assumed.

Modelizing the panel by finite elements and carrying out an elastic-plastic calculation, the strain hardening of the material is necessary to consider: this has been done defining a bilinear curve. This calculation can be performed by proper codes (i.e. ADINA code) which have the occurring facilities. Attention is requested by the non-linearity of the problem, so that an integration of proper size steps needs to be used. For avoiding problem, fictitious orthotropic elements at the extremities has been introduced, so that local effects, due how the load is applied, are not significant on the strains.

By means of this procedure a collapse load, Pp, has been found. This is identified with the load for which mathematical convergence during iterations is not more found. The obtained solution is considered reliable if the load Pp satisfies the following disequation:

$$Py \leqslant Pp < Pc \quad . \qquad (11)$$

Being Py and Pc, respectively, the yielding load and the collapse load determined by means of the beam theory, as briefly shown below.

Applying the beam theory for a beam with compression load at the extremities, the following main results are obtained:

(i) the slope of the elastic zone of the present characteristic curve, given by:

$$K = P/[(Pd(1-\nu^2)/Et) + fo^2 \cdot \pi^2 \cdot (1/(1-\beta^2)-1)/4d] \qquad (12)$$

(ii) the load that is needed for yielding to begin, given by:

$$Py^2 - (P_E + 3 \cdot fo \cdot P_E/t + \sigma y \cdot t) \cdot Py + \sigma y \cdot t \cdot P_E = 0 \qquad (13)$$

iii) the load that is needed for collapse to be reached, given by::

$$Pc^3 - (P_E)Pc^2 - (\sigma y \cdot t)^2 (2 \cdot P_E \cdot fo/\sigma y \cdot t^2 + 1) \cdot P_c + (\sigma y \cdot t)^2 \cdot P_E = 0 \qquad (14)$$

where:

- P_E is the Eulerian critical load for a beam with its ends both clamped and compression loaded: $P_E = P_{cr} = 4\pi^2 EJ_{MIN}/(1-\nu^2)d^2$;
- σy is the yielding stength of the liner material;
- β is equal to P/P_E.

The above results are obtained by application of the beam theory, considering an ideal elastic-plastic material and then the corresponding interaction equation for rectangular sections [3]: $(Pc/Ps)^2 + (M/Ms) = 1$.

Determination of the maximum strain.

The displacement (x_1) of the studs delimitating the buckled region of the liner is found by the intersection on the two characteristic curves determined as said in chapter 5 (see figure 10).

It has been already outlined that, since the shear stiffness of the studs changes versus the plant life, the characteristic load vs. deflection for the studs also is shifted; then, for a constant load condition (for example, $\Delta T_{EFF}(+)$, as in figure 10), the crossing point of the two characteristics also changes its position. So, the displacement of the studs delimitating the buckled zone trends to grow versus the time.

Beside this, the variability of load conditions determines a further change of the displacements of the studs delimitating the buckled panels. In fact, the characteristic curves (of the studs and of the panels) corresponding to the load condition $\Delta T_{EFF}(-)$

present a pattern such as that shown in the left region of the figure 10, so that the intersection point passes from A to A'.

Therefore, when the load condition changes, passing from $\Delta T_{EFF}(+)$ to $\Delta T_{EFF}(-)$, the compatibility point passes from A to A' (see Figure 10) following a path generally non linear (as the problem is non linear).

Besides, it must be noted that, if the liner is subjected to the load condition $\Delta T_{EFF}(-)$ after $\Delta T_{EFF}(+)$, the characteristic curve of the studs corresponding to $\Delta T_{EFF}(-)$ does not intersect the ordinates axis in the point corresponding to P=0. But, owing to the plastic deformation due to the previous load condition (δp in figure 10), this point is shifted of the amount δp in the positive direction of the ordinates axis.

Repeating this procedure step by step, three situations can be experienced:

(a) a situation such that the panel characteristic crosses the studs characteristic only in its own linear portion. In such a case the structure shakes-down in the elastic behaviour: any other plastic strain shall not be experienced by the liner ;

(b) a situation such that an equilibrium condition is reached. In such a case the plastic strains due to the load $\Delta T_{EFF}(+)$ are entirely saved in the next unloading phase (load $\Delta T_{EFF}(-)$): then the structure shall experience plastic fatigue;

(c) an equilibrium situation is never reached: then the plastic strains shall grow continuously up to the rupture.

Only when situation (a) shall be experienced a maximum strain may be determined. The other two situations are both unacceptable.

By means of the described graphical method the maximum displacement of the extremities of the buckled panels can be determined shifting homothetically the panel characteristics, corresponding to each load condition, owing to cyclic repetition of load and unload.

7. Determination of the shake-down load.

Because the shake-down occurs, it needs that the collapse load of the buckled panel satisfies a suitable condition.

The situation is schematized in figure 11, where:

- a and a' represent the characteristics load vs. deflection of the studs at the end of life corresponding, respectively, to the load conditions $\Delta T_{EFF}(+)$ and $\Delta T_{EFF}(-)$;
- b and c represent the characteristics of the panels for each load condition;
- b' and c' represent the final position of the previous curves for each load condition.

Assuming that the load Pp for which yielding begins, in the case $\Delta T_{EFF}(+)$, is defined by the point A on curve b, shake-down is possible only if the curve b' crosses the curve a through a point A' with the same abscissa than A and the curve C reaches a position c' such as it intercepts the curve a' through a point B whose abscissa has an absolute value which satisfies one of the following conditions:

(a) If $P_{p(stretching)} \geqslant P_{p(compression)}$:

$$|X_{B'}| \leqslant P_{p(stretching)} \qquad (15)$$

(b) If $P_{p(stretching)} < P_{p(compression)}$:

$$|X_{B'}| \leqslant |X_A|$$

$$|X_{B'}| \leqslant P_{p(stretching)} \; . \qquad (16)$$

8. Results.

By means of the described graphical method the maximum displacements of the extremities of the buckled panel can be determined. These displacements are related to the strains reached in the most stressed zone (the mid-length section). These strains are calculated by means of the described F.E. calculation.

The main remark to point out is that the proposed method gives a tool to evaluate the maximum strain due to cyclic variation. Therefore the results already include the fatigue aspects of the problem, since for the liner the fatigue is essentially a strain controlled phenomenon.

The results so obtained can be used to perform the structural verification of the liner in compliance with ASME requirements.

The used allowable limits for studs displacements are the same of ASME Code.

The allowable limits for strain have been assumed greater than those specified in the code because it refers only to the elastic strain.

The assumed strain limits for CIRENE application have been stated equal to:

$$\varepsilon_{ALL} = A\ (\%)/10^{4} = 21.1 \times 10^{-3}.$$

REFERENCES

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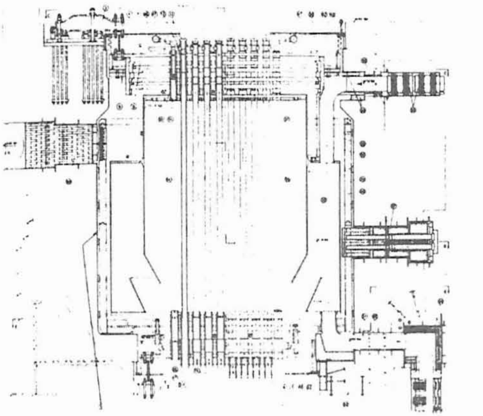
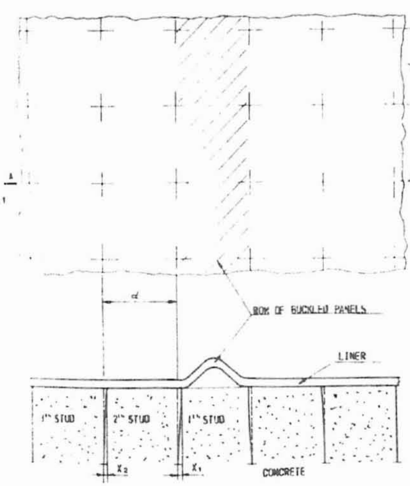
/2/ Y.N. DOYLE, S.L. CHU "Some structural considerations in the design of nuclear containment liners", N.E.D. 16 (1971).

/3/ MC GUIRE "Steel Structures", Mc Graw-Hill.



...URE 1: Sectional view of the calandria of CIRENE Reactor: the liner has been specified as particular 1.



Schematization of a liner anchored to concrete by studs with an initial planarity error.

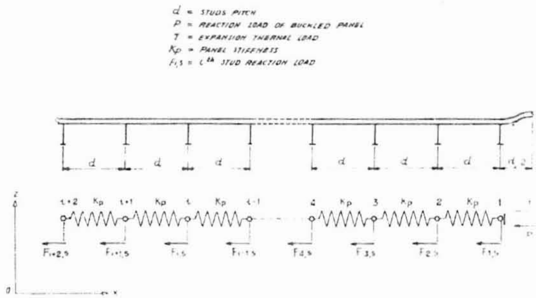


FIGURE 3: Model of the liner used to determine the displacement of the studs contiguous to the buckled panels of liner.

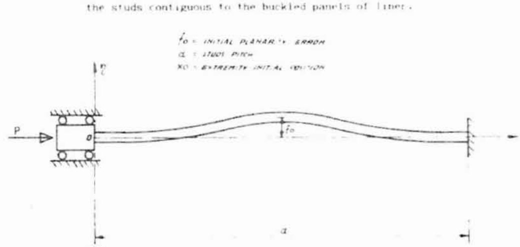


FIGURE 4: Model of a buckled panel of liner, used to valuate the displacement of its extremities us the applied load.

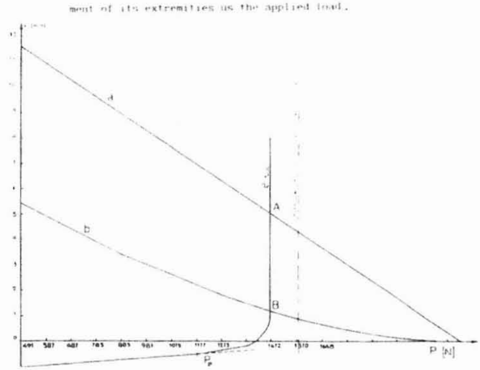


FIGURE 5: Example of intersection of the studs and panel characteristic

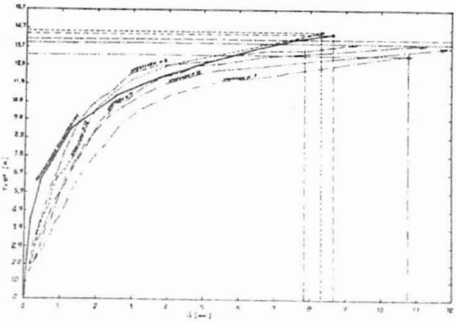


FIGURE 6: Comparison among experimental and manifacturer static shear characteristic for anchor studs.

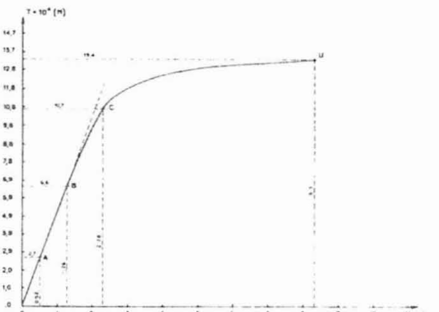


FIGURE 9: End-of-life shear characteristic of anchor studs based on experimental cyclic loading.

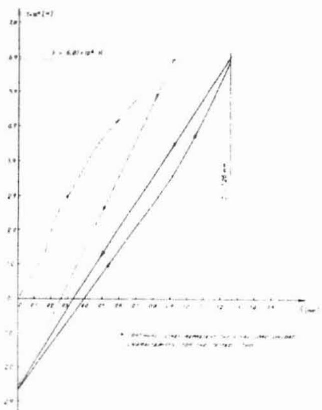


FIGURE 7: Example of the history vs. time of the anchor shear stiffness when subjected to a certain number of cyclic oscillation of the load from zero to the 50% of their rupture value.

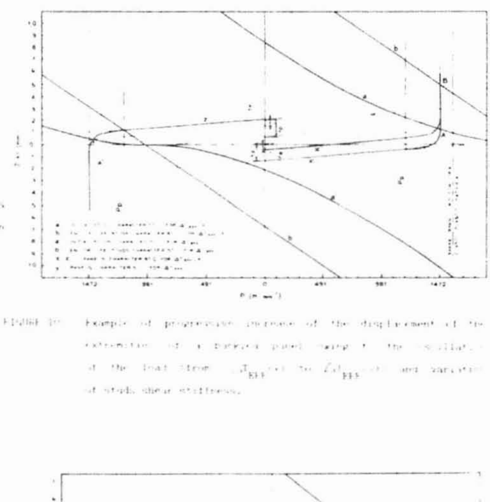


FIGURE 10: Example of progressive increase of the displacement of the extremities of a facade panel owing to the oscillation of the load from T_{EFF} to T_{EFF} and variation of studs shear stiffness.

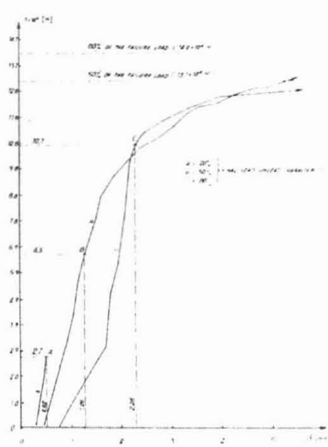


FIGURE 8: Envelope curves for many studs subjected to cyclic repetition of a load whose amount varies from zero to 20%, 50%, 80% of the rupture value.

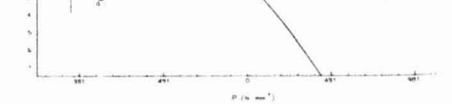


FIGURE 11: Schematization to show how obtaining the shake-down limit

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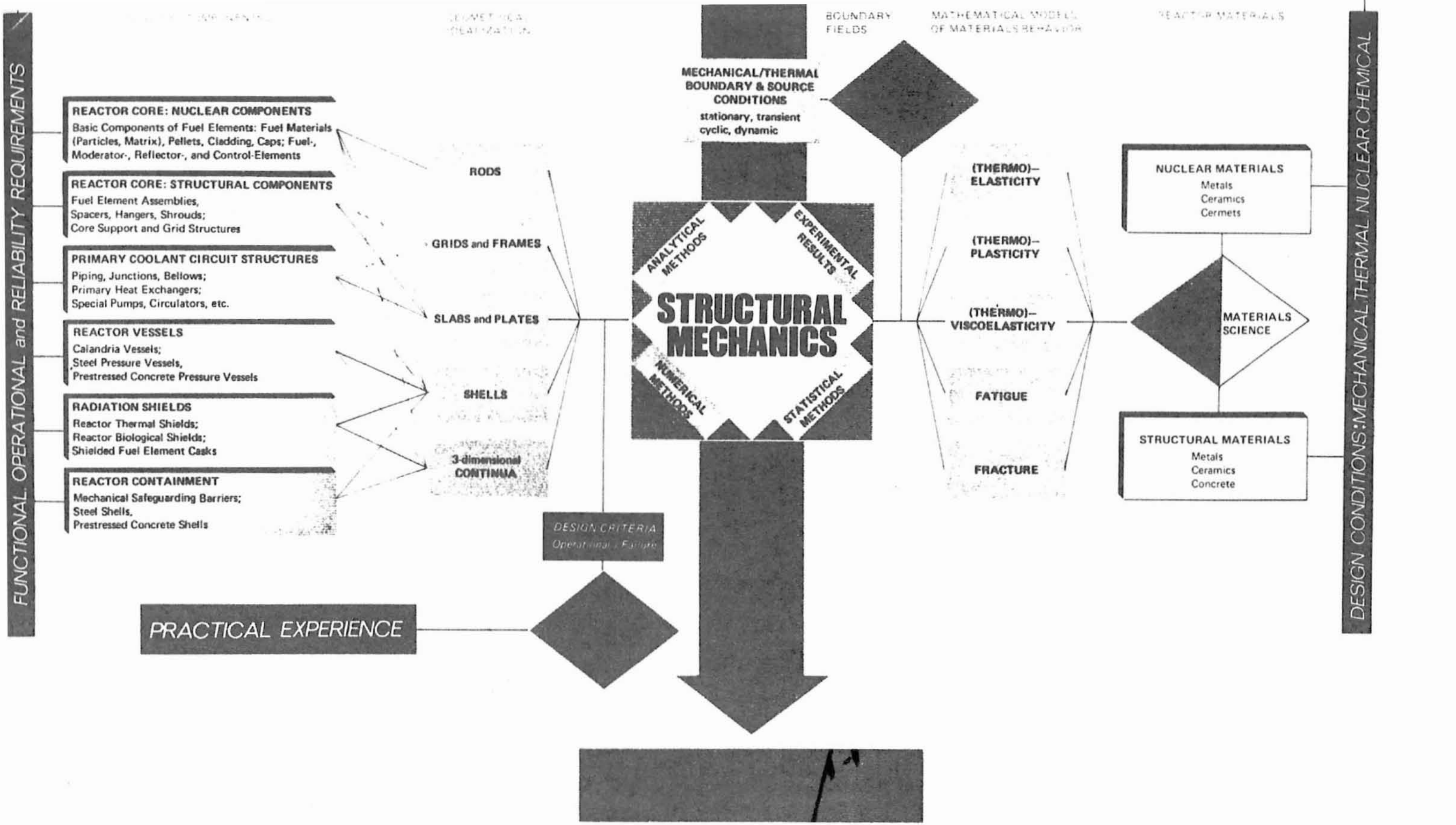

FUNCTIONAL OPERATIONAL and RELIABILITY REQUIREMENTS
REACTOR CORE: NUCLEAR COMPONENTS
Basic Components of Fuel Elements: Fuel Materials (Particles, Matrix), Pellets, Cladding, Caps; Fuel-, Moderator-, Reflector-, and Control-Elements
REACTOR CORE: STRUCTURAL COMPONENTS
Fuel Element Assemblies, Spacers, Hangers, Shrouds; Core Support and Grid Structures
PRIMARY COOLANT CIRCUIT STRUCTURES
Piping, Junctions, Bellows; Primary Heat Exchangers; Special Pumps, Circulators, etc.
REACTOR VESSELS
Calandria Vessels; Steel Pressure Vessels, Prestressed Concrete Pressure Vessels
RADIATION SHIELDS
Reactor Thermal Shields; Reactor Biological Shields; Shielded Fuel Element Casks
REACTOR CONTAINMENT
Mechanical Safeguarding Barriers; Steel Shells, Prestressed Concrete Shells
RODS
GRIDS and FRAMES
SLABS and PLATES
SHELLS
3-dimensional CONTINUA
BOUNDARY FIELDS
MECHANICAL/THERMAL BOUNDARY & SOURCE CONDITIONS
stationary, transient cyclic, dynamic
ANALYTICAL METHODS
EXPERIMENTAL RESULTS
STRUCTURAL MECHANICS
NUMERICAL METHODS
STATISTICAL METHODS
DESIGN CRITERIA
MATHEMATICAL MODELS OF MATERIALS BEHAVIOR
(THERMO)–ELASTICITY
(THERMO)–PLASTICITY
(THERMO)–VISCOELASTICITY
FATIGUE
FRACTURE
NUCLEAR MATERIALS
Metals
Ceramics
Cermets
MATERIALS SCIENCE
STRUCTURAL MATERIALS
Metals
Ceramics
Concrete
DESIGN CONDITIONS: MECHANICAL THERMAL NUCLEAR CHEMICAL
PRACTICAL EXPERIENCE