PWR Fuel Assembly Grid External Stiffness Determination from Dynamic Crush Tests

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1. INTRODUCTION

For the Design Basis Accident grid integrity verification, the maximum compression force undergone by the grid must not exceed the dynamic crush load at operating temperature. This verification of grid integrity under given accident conditions is therefore dependent both on its crush load and on its external stiffness. This stiffness can be determined from dynamic crush tests, before the crush limit is reached. However, stiffness is not measured directly, but deduced from a model of the grid behaviour which is necessarily approximate, and which involves several measured parameters ; this may lead to a large scattering of results, either for several tests, or when different methods for determination are used. The dynamic values may also be notably different from those obtained with static tests, although stiffness should not depend on such conditions, unlike the stability limit.

The aim of this paper is to demonstrate that a reasonable consistency between the different determinations of stiffness can be obtained by using a linear model of grid compression, provided that approximations and disturbing effects are clearly identified, and controlled or corrected.

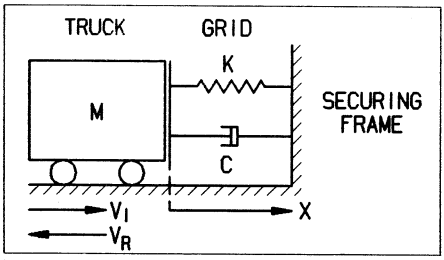
2. TEST CONDITIONS

The grid is horizontal and secured on one face (outer strap) to a very rigid frame, with the other faces free to move. A mass is made to impact the grid at the opposite face, with a flat side overlapping the grid face, and this mass is generally equivalent to that of an assembly span (≃ 90 kg). The test involves gradually increasing impact velocity until crushing takes place, which allows a study of the grid behaviour within the elastic range. Setting the grid in an oven allows tests at operating temperature (≃ 315°C), which are the only ones to be considered hereafter.

The motion is pendular in most test facilities, with the mass hanging from four hinged rods in order that the mass and grid faces remain parallel ; but the motion includes a small vertical translation, and probably slight rotations about a vertical axis. FRAMATOME has recently developed a "linear" device in which the mass is a truck moving on rails and accelerated by means of a counterweight : parasitic motions are then widely reduced, and precise setting or measurement (optical) of impact velocity can be performed. The facility includes a continuous recording of force and displacement during impact, as well as a complete digital data processing system.

3. *METHODS FOR DETERMINATION WITH A LINEAR MODEL*

3.1 Principle



The grid model consists of a spring with stiffness K and a dashpot with damping coefficient C, in parallel, as displayed on the opposite diagram. During the compression, the mass M remains in contact with the grid, thus leading to a standard linear oscillator whose equation is :

$$\left.\begin{array}{l} M\ddot{X} + C\dot{X} + KX = 0 \\ \text{with initial conditions } X(0) = 0 \text{ and } \dot{X}(0) = V(0) = V_I \end{array}\right] \quad (1)$$

The compression force on the grid is :

$$F = - M\ddot{X} \quad (2)$$

and we define F_{max} as the maximum elastic force :

$$F_{max} = KX_{max} \quad (3)$$

which is obtained when $\dot{X} = V = 0$. The impact ends at time T when the mass is again free to move with the return velocity $-V_R$, thus when F and therefore $\ddot{X}$ vanish because of the balance between elastic and damping forces ; then there is a residual displacement, and T is smaller than the half of the pseudo-period. The model behaviour is summarized by the F(t) and F(X) curves, on figures 1 and 2, with the damping ratio $\zeta = C/2\sqrt{KM} = 0.1$.

The mathematical derivation shows that both stiffness and damping can be determined from the following measured parameters :

- M and V_I, which characterize the impact conditions,
- two parameters selected from F_{max}, T, and the restitution coefficient :

$$\varepsilon = \frac{V_R}{V_I} \quad (4)$$

which finally leads to three dynamic determinations.

Obviously, stiffness can also be obtained from :

$$K = \frac{F_{max}}{X_{max}} \quad (5)$$

but this determination is not truly dynamic since neither time nor velocity are involved, and it does not yield damping ("pseudo-static" determination).

The interpretations of the tests show that damping ratio is relatively small, say less than $\zeta = 0.1$, and ζ^2 is then assumed to be negligible with respect to 1. In this case, many mathematical equations are simplified, and F_{max} can be considered as the maximum total compression force (relative error is less than $2\zeta^2$), which is easier to determine from data processing. The grid inertia is also neglected with respect to M, and there is actually no systematic difference between force measurements on both sides of the grid.

3.2 Energy and time methods

Stiffness determination from F_{max} and ε is performed with the (only) exact formula :

$$K_E = \frac{F_{max}^2}{M V_I^2 \varepsilon} \quad (6)$$

where subscript "E" stands for "energy method", because formula (6) is equivalent to the energy conversion rate from kinetic to potential form, during the loading phase :

$$\frac{1}{2} \frac{F_{max}^2}{K} = \varepsilon \left(\frac{1}{2} M V_I^2\right) \quad (7)$$

In the "time method", stiffness is determined from T and ε by :

$$K_T = \frac{(\pi - 2\zeta)^2 M}{T^2} \quad (8)$$

with the value of damping ratio :

$$\zeta = \frac{\pi - \sqrt{\pi^2 + 8 \ln \varepsilon}}{4} \quad (9)$$

which can also be associated to K_E since it depends upon ε only.

3.3 Coupled determination

When F_{max} and T are used, the determination is said to be "coupled" since damping depends on both parameters. Damping is obtained from $K_E = K_T$, which yields the following equation for the coupled value ε_c of ε :

$$\varepsilon_c \frac{\left(1 + \sqrt{1 + 8/\pi^2 \ln \varepsilon_c}\right)^2}{4} = \left[\frac{F_{max} T}{\pi M V_I}\right]^2 \equiv \frac{K_E^o}{K_T^o} \quad (10)$$

where K_E^o and K_T^o correspond to zero damping in (6) and (8). Stiffness K_C is then determined from (6) and damping ratio ζ_c from (9), with $\varepsilon = \varepsilon_c$.

As K_E increases and K_T decreases when damping increases, damping is positive or zero only if $K_T^o \geqslant K_E^o$. This consistency criterion can be generalized by considering that in equation (7), energy creation occurs when K is smaller than K_E^o ; therefore, any value K should satisfy :

$$K \geqslant K_E^o \quad (11)$$

whatever form of damping is used.

3.4 Integral determination of damping

The damping coefficient C can also be obtained from the evaluation of the work performed by the compression force F during the impact. By neglecting the residual potential energy at time T in the energy balance, with a relative error which is about 5 %, one obtains :

$$C = \frac{\int_0^T F(t)\, V(t)\, dt}{\int_0^T V(t)^2\, dt} \quad (12)$$

The velocity is deduced from the momentum balance, as follows :

$$V(t) = V_I - \frac{1}{M} \int_o^t F(\tau)\, d\tau \qquad (13)$$

and finally C depends on the recording of F only, through integrations (which is favourable from a numerical standpoint). It is noteworthy that momentum balance is well verified, since the computed velocity at maximum displacement does not exceed 2 or 3 % of impact velocity.

4. ALLOWANCE FOR DISTURBING EFFECTS

4.1 Difficulties in direct interpretation of tests

For typical Inconel grids, the minimum estimate of K_E is 5600 daN/mm, the maximum one of K_T is 4000 daN/mm, and the relative difference is larger than 30 % of the average value. The coupled determination yields 4400 daN/mm, but with a slightly negative damping, and neither of the previous values is quite consistent with the best estimate from static tests, i.e. 5150 daN/mm. In the determination of K_E, the force/velocity ratio is chosen as the slope of the straight part which is systematically found on the force-velocity experimental curve, as displayed on figure 5. As on this line velocity remains positive when the force vanishes, the ratio and thus K_E could be favourably decreased by considering each impact ; yet values close to the static one would be obtained for small velocities only, and then K_T would notably decrease, since T increases when velocity decreases. The situation is very similar for the Zircaloy grids.

Finally, an acceptable consistency between the different dynamic determinations is obtained only when damping is neglected (K_E^o is close to K_T^o) ; yet this is not completely realistic, and also yields a somewhat smaller value than the static one, more especially when averaging over several impacts. Such a situation may partly explain the quite small values (3500 daN/mm or even less) which have been obtained in some determinations for Inconel grids.

4.2 Disturbing effects

The damping value is probably too large when deduced from ε (at least 8 % of critical, and often more than 10 %), thus increasing the gap between K_E and K_T. This may originate in energy absorption by the test facility itself, but the measurement of V_R can also be disturbed by the vibrations resulting from the impact. Therefore ε is not considered as a very reliable parameter, and either the coupled determination is used, or damping is evaluated with the integral determination (12), in which it is more closely related to grid behaviour throughout the impact.

Yet the violation of consistency criterion (11) is not related to excessive (or non-viscous) damping, but to non-linear effects, which are obvious on the F(t) and F(X) experimental recordings when compared to the theoretical curves (figures 1 to 4), and on a typical F(X) curve under static conditions (figure 6). Such a non-linearity may result from the complex structure of the grid, in which fuel rods and guide thimbles are not fully loaded by small compression forces, but this is likely to be masked by a "setting effect", since non-linearity appears mainly at the beginning of the impact on figures 3 and 4 ; it is also obvious that the theoretical non-zero force at the very beginning of impact cannot be obtained experimentally. Non-linearity can also be strongly enhanced for some grids which have been rejected for in-assembly use, because of geometry defects such as non-parallel outer straps in the vertical direction (pyramid frustum shape). But with an acceptable grid geometry, it is always possible to eliminate a "preliminary part" of the impact, up to time t_o or displacement X_o, and to perform a determination with the remaining linear range, as for usual static "tangent" determinations (as the value in § 4.1).

Although this stiffness is larger than the average "secant" one (and thus conservative), it is the only one to be fully consistent, since related to the real grid behaviour, and independent of an averaging range.

4.3 Corrections due to non-linearity

The impact duration T should be reduced by t_o, which can be determined either directly from the F(t) curve, or from X_o on the F(X) curve by assuming that it is equal to X_o/V_I, or from the measured monotone decrease in T when V_I increases, by assuming that this variation results from the decrease in t_o with constant X_o. The different methods yield the same order of magnitude, i.e. a 10 % reduction in most cases, therefore a 20 % increase in K_T.

The force/velocity ratio determination as described in § 4.1 is equivalent to the equation :

$$F_{max} = \sqrt{K_E^o M}\,(V_I - V_{Io}) \qquad (14)$$

which does not mean that non-linearity is included in V_{Io} only, since the slope is also increased for grids with notable geometry defects. Moreover, equation (14) is equivalent to the energy balance (7) for zero damping, but with $(V_I - V_{Io})^2$ in the kinetic energy, and thus with a "preliminary" energy loss :

$$E_o = M\,V_{Io}\,(V_I - V_{Io}/2) \simeq M\,V_{Io}\,V_I \qquad (15)$$

which is found to become excessively large when V_I increases. It is more likely that E_o will remain approximately constant, with a hint given by the static case (figure 6) : for any force larger than a small value F_o, the linear form (7) of potential energy appears to be reduced by a constant value E_o, with respect to the total potential energy. By expressing :

$$E_o = \frac{1}{2} M\,V_o^2 \qquad (16)$$

the energy balance yields the equation :

$$F_{max}^2 = (K_E^o M)\,(V_I^2 - V_o^2) \qquad (17)$$

which proves suitable since a straight part is still observed on the curve when using the squared values, as displayed on figure 7. The value of K_E^o is favourably decreased, and as V_o only is significantly increased with geometry defects, the determination should be almost free from the influence of non-linearity. For grids with an acceptable geometry, the reduction in K_E^o is less than 10 %, but it is not negligible for consistency achievement.

5. *STIFFNESS DETERMINATION*

5.1 Verification of determination consistency

From the previous considerations, this verification can be performed by comparing the coupled and the static determinations. For sets of grids whose properties can be considered as homogeneous, one obtains the following results :

GRID TYPE	K static (daN/mm)	K_C (daN/mm)	DAMPING (100 x ζ_C)
Inconel	5150	5100	6.2
Zircaloy	2300	2500	6.5

Consistency results both from similar stiffness values and from damping values which are not negligible, although smaller than for most determinations from ε (see also § 5.2).

5.2 Selection of a practical method - Influence of damping

The determination of the force/velocity ratio is certainly more reliable than that of impact time, and consequently the energy method is proposed for practical use. This conversely requires a more direct damping determination, for which the integral method seems reliable for reasons given in § 3.4 and 4.2, and also because it yields the smallest values (3 to 5 % of critical), and then might be more free from parasitic energy absorption. Yet it may represent a lower bound since larger values (similar to those in § 5.1) can be obtained when determining V_R and ε from the momentum balance (13), which is involved in the integral method, instead of from direct measurement.

Therefore an accurate damping determination remains difficult, just because the grid response is a forced one, but this conversely leads to a limited influence on stiffness determination and thus on the maximum force under accident conditions. Furthermore, as K_E increases with damping, using this damping in the grid model for accident simulations tends to offset its influence through stiffness in the maximum force. Finally, damping should be included in stiffness determination to improve consistency, but a very good accuracy is unnecessary provided that the value remains within a reasonable range.

5.3 Application of the energy method

The determination is performed with results from the most recent tests, which correspond to figure 7, from which K_E^o can be determined. The value of damping coefficient C obtained by the integral method is averaged over the impacts used for the K_E^o determination. Then ε in equation (6) is deduced from the reciprocal expression of (9) :

$$\varepsilon = e^{-\zeta(\pi - 2\zeta)} \qquad (18)$$

and as ζ depends on both C and K, iterations are necessary, but a single one yields a convergence to within 1 %. The determination is summarized in the following table :

GRID TYPE	K_E^o (daN/mm)	C(kg/s)	K_E(daN/mm)	100 x ζ
Inconel	4250	5400	4800	4,1
Zircaloy	2350	3500	2650	3,7

From the considerations in § 5.2, slightly larger values could be proposed, which means that the Zircaloy grids are more rigid than those in § 5.1.

6. *CONCLUSIONS*

Consistency of stiffness determination is primarily based on the elimination of non-linear behaviour for small compression forces, and the most reliable determination is obtained from the ratio of the maximum compression force to the impact velocity. Testing grids with restricted geometry defects is also favourable. Damping is included and should be determined from energy and momentum conservation throughout the impact, rather than from the return velocity only, but high accuracy is illusory, and unnecessary if the value remains realistic.

The grid stiffness is then determined with a relative error which should not exceed 10 %. In round numbers, the proposed values are 5000 daN/mm for Inconel grids, half that for Zircaloy grids, and damping is about 5 % of critical. Due to non-linear effects, these stiffness values are larger than the average ones over the total compression range, thus leading to a conservatism margin which could be reduced but only with caution.

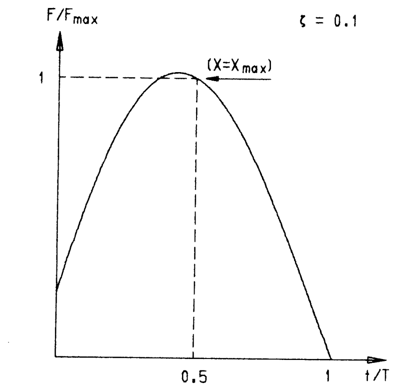


FIG. 1 - THEORETICAL RELATIONSHIP BETWEEN DIMENSIONLESS FORCE AND TIME.

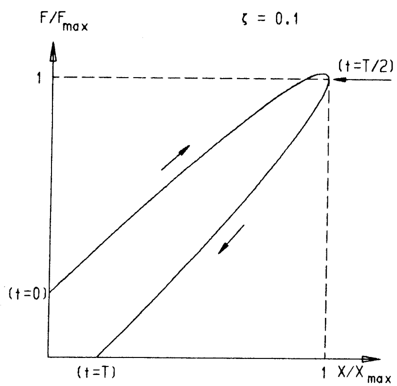


FIG. 2 - THEORETICAL RELATIONSHIP BETWEEN DIMENSIONLESS FORCE AND DISPLACEMENT.

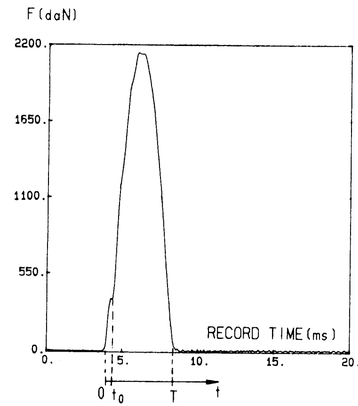


FIG. 3 - EXPERIMENTAL FORCE VERSUS TIME RECORDING (INCONEL GRID, V_I = 0.35 m/s)

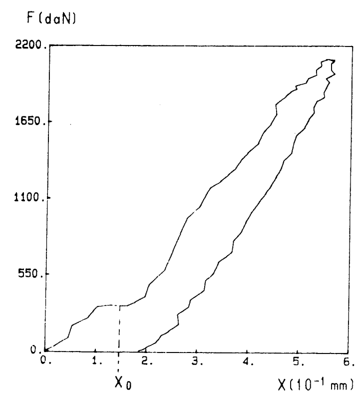


FIG. 4 - EXPERIMENTAL FORCE VERSUS DISPLACEMENT RECORDING (INCONEL GRID, V_I = 0.35 m/s)

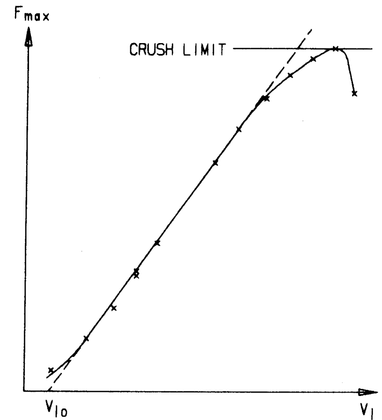


FIG. 5 - TYPICAL CURVE OF MAXIMUM FORCE AS A FUNCTION OF IMPACT VELOCITY

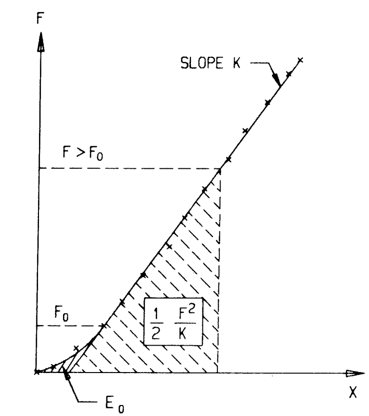


FIG. 6 - TYPICAL CURVE OF FORCE AS A FUNCTION OF DISPLACEMENT UNDER STATIC CONDITIONS.

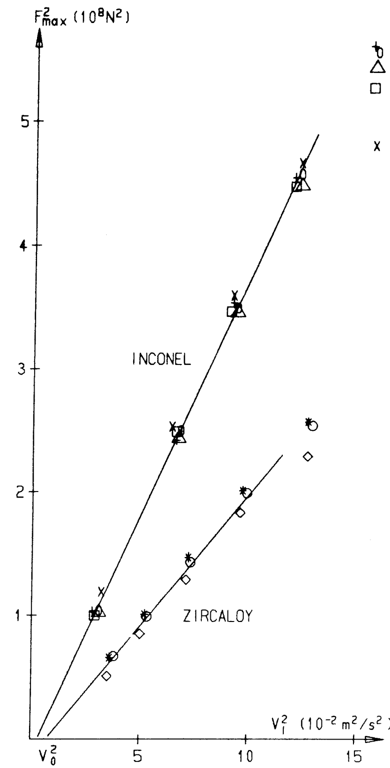


FIG. 7 - RELATIONSHIP BETWEEN THE SQUARED VALUES OF MAXIMUM FORCE AND IMPACT VELOCITY, FOR FIVE INCONEL AND THREE ZIRCALOY GRIDS.