STUDY AND MEASUREMENT OF IMPACT DAMPING
IN PWR REACTOR COOLANT SYSTEM SEISMIC
AND ACCIDENT RESTRAINTS

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SUMMARY
This paper describes the program, undertaken jointly by WESTINGHOUSE NUCLEAR INTERNATIONAL and the UNIVERSITE LIBRE de BRUXELLES, to determine the impact damping in the reactor coolant system lateral restraints of WESTINGHOUSE design.
1. INTRODUCTION

In PWR nuclear power plants, the large components and primary piping are restrained by steel bumpers and tie bars anchored in concrete. Since the purpose of these is to restrict seismic and accident deflections, they are designed to withstand high impact loads.

Studies of similar collisions have shown that the energy imparted to the restraining system is not completely returned to the missile after impact. Colliding bodies absorb energy by various means such as: local plasticity, material hysteresis, friction, vibration.

Energy absorption associated with impact contributes to the damping of the system dynamic response. In the analytical models, this contribution, hereafter called "impact damping", is simulated by putting equivalent viscous dampers in parallel with the springs representing the restraint stiffnesses.

The ratings of these dampers is of paramount importance and must represent realistically and conservatively the amount of energy absorbed during impact.

Considering the complexity of the phenomena involved, testing, on reduced scale models was considered a reasonable approach to produce realistic measurements of impact damping.

This paper describes the program, undertaken jointly by WESTINGHOUSE NUCLEAR INTERNATIONAL and the UNIVERSITE LIBRE de BRUXELLES to determine the impact damping in the PWR reactor coolant system lateral restraints. This program includes a feasibility study, the design of the test rig and the measurements.

2. STUDY OF IMPACT DAMPING

2.1 System Description

A view of a typical steam generator support system is given in Figure 1. As can be seen, there are four vertical columns, a set of lower lateral restraints, and a set of upper lateral restraints. This system, while allowing free thermal expansion, restricts the lateral motion due to earthquake or postulated pipe ruptures. Spherical bearings at the top and bottom of the column supports permit unrestrained horizontal thermal movement. However, once in the hot position, complete lateral support is provided in all directions by hydraulic shock absorbers or "snubbers" and structural restraints or "bumpers".

Lateral support for the main coolant pump and whip restraint for the main coolant piping are provided in a similar way via tie bars, bumpers and snubbers anchored in concrete.

The bumpers and tie bars are shimmed during hot functional testing to obtain minimum clearances during normal operation.

These devices, which may be exposed to large impact loads due to the presence of gaps, are the subject of this paper.

2.2 Coefficient of Restitution: C

The basic laws of shock have been comprehensively described by RAPIN (1), who introduces Newton's assumption: "The shock impulse after impact is proportional to the shock impulse before impact".

\[ I_1 = C I_0 \]  
(1)

In terms of the missile (i.e. the steam generator) and target (i.e. one SG lateral bumper) velocities, eq. (1) becomes:

\[ C = - \left( \frac{V_1 - v_1}{V_0 - v_0} \right) \]  
(2)
If the target is at rest before \(v_o = 0\) and after \(v_i = 0\) impact:

\[
C = -\frac{V_i}{V_o}
\]

(3)

The coefficient of proportionality \(C\), called Newton's coefficient of restitution, varies between zero and one, depending on the amount of energy absorbed during the shock.

For the one degree of freedom (DOF) system of Figure 2, where the deformation is assumed to be represented by a damped sinusoidal half wave, the coefficient of restitution is related to the critical damping ratio by:

\[
C = e^{-\frac{k_o}{\sqrt{1 - \xi^2}}}
\]

(4)

This relation is useful because:

- the representation of the reactor coolant system restraints used in the dynamic analyses is similar to the system of Figure 2,
- The degree of impact damping is known once 'C' is determined.

2.3 Causes of Damping

References were of little help for estimating a coefficient of restitution applicable to our equipment and restraints. Order of magnitude is indicated, as in (1) and (2), concerning simple forms and materials, such as steel balls. However, the discrepancies from reference to reference are too large and it is also evident that the following essential factors have not been properly taken into account in these simple cases:

- **Materials**: Two materials contribute to the impact damping discussed in this paper. They are: the equipment and restraint steel and the reinforced concrete to which the restraints are anchored (Figure 1).
  
  (a) Steel: energy absorption in steel occurs in the form of elastic hysteresis. This phenomenon is accentuated for steels having low yield stress and/or having fine grains.
  (b) Concrete: The energy absorption mechanism in concrete is still obscur. It seems to be accompanied by the development of microcracks at the many interfaces between cement and aggregates. Consequently, this phenomenon should be more apparent for concretes having small aggregates.

- **Stress Level**: Most of the structures treated in this study have been designed to undergo two levels of load:
  
  (a) One lower bound level, hereafter called "UPSET", which consists of an OBE earthquake after which the plant has to return to normal function.
  (b) One upper bound level, hereafter called "FAULTED", which consists of the postulated rupture of one of the large pressurized pipes (primary coolant piping, main steam line, etc.). Subsequent local permanent deformations are tolerated, provided that the capability to bring the reactor to a safe shutdown condition and maintain it there are not jeopardized.

- **Local Plasticity**: The influence of local plasticity on damping and its development during impact are both evident. From the discussion on stress level, it appears that faulted condition design rules and allowable stresses likely lead to local yieldings. For example, in tie bars, plastic deformations are predicted in the vicinity of the eyelet holes (3).

- **Friction**: Friction results in slip damping in all joint interfaces. Slip damping is again predominant in tie bars, where the joint interfaces are more numerous than in bumpers.
- Impact Velocity: Impact velocity can have a considerable effect since it determines the intensities of the stress waves propagating through the colliding bodies and may influence the area enclosed in the material hysteresis curve.

- Vibration: After contact has ceased, vibration can persist both in the missile and in the target. The vibration energies are not dissipated and thus are felt as an energy loss which contributes to the impact damping. It has been demonstrated by LEE [4] that the significance of this phenomenon increases as the impact duration is short compared to the colliding bodies first natural periods.

The number and complexity of the phenomena involved in the impact damping of structures lead us to consider testing on a scale model to be the best way to proceed. The remainder of this paper describes the tests and their results. First of all, however, a feasibility study was conducted in order to:

- Select the most unfavorable impact which might occur between the primary system and the restraints,
- derive from this case the test parameters and the properties of the scale model. These parameters indicated by which means testing should be carried out and which instrumentation should be used to measure the coefficient of restitution.

3. FEASIBILITY STUDY

3.1 Bumper Studied: The Prototype

The most unfavorable restraint, i.e. the one with the highest restitution capability (or minimum impact damping), was selected on the basis of the criteria described in paragraph 2.3. This restraint was the steam generator lower lateral plain steel bumper of Figure 3. The main reasons for this choice were:

- bumpers have higher restitution capability than tie rods where local plasticities and joint interfaces are more numerous,
- the corresponding missile, i.e. the steam generator at the tube sheet level, is very stiff. Energy absorption via missile vibration is consequently minimized.
- a plain bumper has less joint interfaces and smaller residual rolling stresses compared to bumpers made of milled shapes and welded stiffeners.

The significant parameters related to this "PROTOTYPE" are:

- Materials:
  (a) Steel: high-strength low-alloy structural steel ASTM A-588
  Minimum yield stress = 50 KSI;
  Minimum tensile strength = 70 KSI;
  Modulus of elasticity $E_a = 20.6 \times 10^{10}$ N/m$^2$
  (b) Concrete: Modulus of elasticity $E_b = 2.3 \times 10^{10}$ N/m$^2$

- Load Level: UPSET: $F = 2670$ kN
  FAULTED: $F = 15403$ kN

- Impact Velocity: $V_o = 0.53$ m/sec

- Impact Duration: $\tau_p \geq 0.013$ sec.
3.2 The Scale Model

Basically, the scale model is a geometrical reduction of the prototype. However, considerations such as materials, fabrication of the scale model, impact velocity and mass of the missile had also to be addressed. These considerations were approached with a view to defining test conditions more conservative than those defined in paragraph 3.1.

- Fabrication: The scale model was purposely modified in order to avoid too high complexity of fabrication, i.e.:
  - Shim plate(s), used in prototype to set the clearance between equipment and restraint, and concrete reinforcing bars were not modelled. These two simplifications resulted in a reduction of the number of joint interfaces responsible for friction and micro-cracking.
  - The modelling of the supporting concrete structure was limited to the compressed zone. This zone is so stiff that the energy absorption due to the target vibration was expected to be negligible in the model.

- Materials and Impact Velocity: With these simplifications, only internal damping such as hysteresis and micro-cracking was reflected in the model.
  As these phenomena are sensitive to material properties (E, ρ), stress level (σ) and impact velocity (V) (see paragraph 2.3), these parameters were maintained in the scale model.

- Other Parameters: The geometrical scale factor and the mass of the missile could only be set on the basis of a dimensional analysis.

3.3 Dimensional Analysis

For this study, the one dimensional model of Figure 2 was considered.

As discussed in paragraph 3.2, the amount of energy absorbed during an impact depends on the following parameters:

- \( E_a, E_b, \rho_a, \rho_b \): defining the elastic and inertia properties of steel and concrete.
- \( V_o, V_i, \tau \): defining the coefficient of restitution ‘C’
- \( \sigma \): influencing the damping by hysteresis
- \( I_a, I_b \): fixing the scale and proportions of steel and concrete in the model

Seven non-dimensional factors \( \eta_j \) (j = 1 to 7) were constructed from these parameters. They determine univocally the damping phenomenon in the model and their equivalence between prototype and scale model had to be achieved.

By maintaining \( E, \rho, V_o \) and \( \sigma \), it was verified that factors \( \eta_j \) (j = 1 to 6) were also maintained. The condition had still to be satisfied for \( \eta_7 \), or:

\[
\frac{V_o \tau}{I_a} m = \left( \frac{V_o \tau}{I_a} \right) p, \text{ or:} \\
\frac{\tau}{I_a} m = \left( \frac{\tau}{I_a} \right) p
\]  

(5)

Since we had no control on the duration of the impact on the scale model (\( \tau \) m), there was a lack of simultaneity, the consequences of which were studied in paragraph 3.5.

3.4 Dimensioning of the Scale Model

The dimensioning of the scale model was carried out on the basis of the equation of motion of the one DOF represented in Figure 2, in which the damper is neglected. This simplification was necessary since the damper rate was not known.
In such a system, the maximum force resisted during impact is:

$$F_{\text{MAX}} = V_0 x (kM)^{1/2} = a_a Sa$$  \hspace{1cm} (6)

where:

$$1/k = la/EaSa + lb/EbSb$$  \hspace{1cm} (7)

Introducing the linear scale factor $\lambda$, such that:

$$Im = \lambda x Ip \text{ and } Sm = \lambda^2 x Sp$$

and using the data related to the prototype supplied in paragraph 3.1 and Figure 3, eq. (6) and (7) gave:

$$Mm = 4.76 \times 10^4 \lambda^3$$

$\lambda$ was taken equal to 1/20 in order to obtain reasonable values for Mm, F and Im:

$$\lambda = 1/20 \rightarrow \begin{cases} Mm = 5.95 \text{ kg} & \text{lam} = 19.1 \text{ mm} \\ F_{\text{MAX}} = 38.5 \text{ kN} & \text{lbm} = 60.0 \text{ mm} \end{cases}$$

3.5 Lack of Similitude

As discussed in paragraph 3.3, the laws of similitude are met if eq. (5) is satisfied,

$$\tau_m = \lambda \tau_p = 650 \mu s$$

In the one DOF system representing the scale model, the impact duration is approximately equal to one half-period

$$\tau_m \approx \pi (Mm/km)^{1/2} = 260 \mu s$$

Therefore, a lack of similitude had to be expected.

$$\tau_m < \lambda \tau_p$$

Figure 4 indicates that, at equal stress level, the smaller duration of the impact in the scale model results in an increase of rebound velocity. This demonstrates that the lack of similitude increases the conservatism of the measurements made on the scale model, provided that the stress level is not changed.

4. TESTING

4.1 Samples

Sample dimensioning was obtained by reducing the linear dimensions of the bumper represented in Figure 3 by the scale factor $\lambda = 1/20$.

The section of the concrete was enlarged in order to allow stress diffusion in a frustum of 45°.

Each sample was used only once.

Thirty samples were available per tested load level.

Twenty of them were used in identical impact condition to actually establish the coefficient of restitution.

Ten extra samples were available to be used up during possible missile re-calibration (see paragraph 4.4).
4.2 Test Rig

The scheme of the test rig is represented in Figure 5. As can be seen, impact was achieved by simply dropping the missile from a height depending on the magnitude of the initial impact velocity ($V_0$):

$$\Delta = \frac{V_0^2}{2g} = 0.0143 \text{ m}$$

4.3 Measurement of the Restitution Factor

The missile 2 was provided with a reflective bench mark. The missile bench mark was illuminated during fall and rebound by a high frequency stroboscope 8. The corresponding traces were recorded on a high sensitivity emulsion. During the missile travel, the camera 6 moved laterally on a slotted track 7 such that the traces of fall and rebound were not confused.

The missile velocity immediately before ($V_0$) and after ($V_1$) impact, and hence the coefficient of restitution ($C$), were measured from these recorded traces of the bench mark travel.

4.4 Control of the Lack of Similitude

As demonstrated in paragraph 3.5, the lack of similitude would lead to conservative measurements of $V_1$ if

$$\tau_m < \tau_p$$

with $\alpha$ maintained.

This verification, possibly leading to the re-calibration of the missile mass had to be achieved by measuring the impact duration $\tau_m$ and the maximum acceleration during impact, $a_m$, since

$$a_m = \left(\frac{aM}{Sa}\right)m$$

Instrumentation involving accelerometer 3 and oscilloscope were used for that purpose.

4.5 Results

Due to the delay in the delivery of one instrumentation device, the measurements were not completed at the time this paper was written. The most significant results will be made available to the attendees, the day of the presentation.

5. CONCLUSIONS

Since the results were not available, only the conclusions related to the feasibility study were drawn. The phenomena involved in the impact damping of the support structures were reviewed. Their number and complexity lead us to consider testing on a scale model to be a reasonable approach. The scale of the model, the mass of the missile and the force to be resisted during impact confirmed that testing was economically feasible. As the degree of impact damping is known once the coefficient of restitution is determined, the measurements could be made by means of a simple set-up composed of a camera and a stroboscope. However, as the mass of the missile was based on an approximate calculation, it was desirable to measure with an accelerometer the maximum impact stress with a view to possible readjustment of the value of the mass.
SYMBOLS

E  young modulus
C  coefficient of restitution $C = V_f/V_o$
F  reaction force in the bumper
k  compression stiffness
l  length measured in the shock direction
M  mass of the missile
S  bumper cross section area perpendicular to the shock direction
V  velocity of missile
v  velocity of target
ξ  critical damping rate
λ  geometrical scale factor
ρ  mass per unit of volume
σ  maximum stress during the impact
η  factors of similitude
τ  duration of the impact
W  angular velocity
I  shock impulse

INDICES

m  scale model
p  prototype
a  steel
b  concrete
o  prior to impact
i  after impact

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Figure 1
Steam Generator Supports

Bumpers (3)
UPPER LATERAL RESTRAINTS
Snubbers (5)

bumpers (3)
LOWER LATERAL RESTRAINTS

Coolant Inlet
Columns (4)

Direction of Thermal Expansion

Figure 2
One DOF System

Figure 3
Type of Bumper Studied
Figure 4
Influence of Lack of Similitude

Figure 5
Scheme of the Test Rig

Legend
1. rupture mechanism
2. missile
3. accelerometer
4. sample (target)
5. anvil (steel)
6. camera
7. track
8. stroboscope
9. overhead crane
10. lab. floor (concrete + 1 steel beams)
11. foundations (concrete)
12. bench mark