Studies of Pipe Whip and Impact

J.L. Garcia, P. Caumette, J.L. Huet
Commissariat à l'Energie Atomique,
C.E.N. Cadarache, B.P. No. 1, F-13115 Saint-Paul-lez-Durance, France
A. Martin
Framatome, 77-81 rue du Mans, F-92403 Courbevoie, France

SUMMARY

In the design of nuclear power plant facilities, the effects of pipe whip on essential structures and components must be evaluated in the event of impact. It is therefore necessary to validate calculational tools which can provide realistic analyses of :

- pipe whip following breach opening,
- pipe impact.

The present study was made under an agreement between CEA/FRA/EDF[*], it concerns PWR primary pipes, particularly the following aspects :

- Experiment : two tests of pipe whip with impact on rigid structures were performed. The purpose of these tests was to measure the impact loads. Besides, two complementary tests were carried out : a direct measurement of the load applied on the pipe during depressurization and a test of static crush of this pipe.
- Calculation : different calculation models were developed in order to reproduce pipe whips and to obtain impact loads. A simple preliminary analysis, based on the rigid-plastic behavior of the material, provides conservative results. Two different analyses performed with a finite element code are presented below. These calculations use an engineering beam model. The impact is simulated, as in the former analysis, by introducing a local nonlinear stiffness obtained by the static crush test. The agreement between calculations and results of the tests justifies the method used to simulate the impact.

---

[*] CEA : Commissariat à l'Energie Atomique
FRA : FRAMATOME
EDF : Electricité de France

1. INTRODUCTION

In the event of pipe break, surrounding structures may support important loads due to pipe impact. It is therefore necessary to evaluate these loads.

To this end, two tests of pipe whip with impact on rigid structures were carried out at the Cadarache Nuclear Center on Aquitaine II [1, 2]. Different calculations were compared to experimental results.

A beam model was used in analytical **or** finite element calculations. The purpose was to simulate the impact with the help of a local nonlinear stiffness representing the pipe yielding. As the calculation of this stiffness was a complicated matter,the measurement obtained by a static test was used first.

2. TEST PRESENTATION

Three depressurizations were performed on AQUITAINE II facility :

a) two tests of pipe whip with impact on a rigid structure. The structure is supported by four load cells (figure 1) ; its resonant frequency is greater than 6 kHz. The gaps between the pipe and the structure are 0.180 m and 0.270 m, respectively; the impact takes place on the elbow mid-point. The first experiment was recorded with a high-speed camera (5350 frames/second).
The main results are presented on table I and figures 6 to 10,

b) one test of direct measurement of the jet thrust on the pipe during depressurization. The elbow is supported by a structure equipped with a load cell (figure 2). Results are presented figure 4.

These tests were carried out with austenitic stainless steel pipes (AISI 316L).

Mechanical characteristics :

σ_y = 155 MPa

σ_u = 475 MPa

A = 25 %

Pipe specifications :

outside diameter	88.9 mm
thickness	7.62 mm
elbow bending radius	135 mm

Experimental conditions :

pressure	16.5 MPa
temperature	320 °C .

Pipe breaks were initiated by a pyrotechnical device (break opening time lower than one millisecond).

Moreover, a static crush test was performed on an elbow, which was similar to the elbows used in dynamic tests (figure 3). The relationship between applied load and elbow yielding is presented in figure 5.

3. PLASTIC HINGE MODEL

First, the material behavior is assumed to be rigid-plastic. The test section is represented by a cantilever (length L) loaded by the jet reaction at its free end. With these assumptions, a stationary plastic hinge appears :

- at a distance $L_o = \frac{3M_p}{F}$ from the tip ,

  provided $L_o < L$

  M_p plastic resisting moment

  F applied force ;

- at the support, provided $L_o \geqslant L$.

In both tests, the plastic hinge forms at the support. The pipe movement is determined by the following equation :

$$I \ddot{\theta}(t) = F(t) L - M_p \qquad \text{eq. (1)}$$

I is pipe moment of inertia as calculated with respect to the support,

M_p is calculated with dynamic mechanical characteristics of material.

Taking the impact into account, the equation (1) is completed with a reaction force R (impact load) :

$$I\,\ddot{\theta}(t) = [F\,(t) - R\,(t)]L - M_p \qquad \text{eq. (2)}$$

The equation (2) is solved with an interative method ; for each time step, R can be calculated in fonction of θ (t) with the help of the load versus crushing law obtained by the static test.

The characteristics of the whipping and the impact, as calculated with this model, are presented in table II.

4. FINITE ELEMENT ANALYSIS

For pipe whips and impacts, finite element calculations were performed with TEDEL (CEASEMT system [3]). Characteristics of this code are :

- engineering beam model ;
- dynamic calculation with direct integration and possibility of time step adjustment during the calculation ;
- elastoplastic calculation : an equivalent stress is calculated from membrane efforts N and bending moments M ; plastic deformations associated with M and N are determined by application of the normality principle ;
- geometrical nonlinearity with up-dating of the geometry at every step ; the direction of the jet reaction applied to the pipe (presented figure 4) is also determined at every step (follower force).

Two analysis were performed using this code ; the methods employed to calculate the impact were different.

4.1 - First analysis : contact element

A contact element simulates the local behavior of the elbow during impact :

- it only works in compression, when a strain threshold is reached ;
- it has no mass ;
- its behavior law simulated load-yielding relationship obtained by the static test.

When the strain threshold is reached, a contact load is introduced into the dynamic equation of the problem. This dynamic equation is solved by an implicit iterative method [4].

The dynamic mechanical characteristics of the steel were used in this calculation (with a linear strain-hardening law).

As regards the two tests, this analysis is in good agreement with experiments for whipping movement and impact (table III and figures 6, 7). One may notice that impact must be calculated with a very small time step (25 μs).

4.2 - Second analysis : unilateral constraints

In this analysis, the local behavior of the elbow is simulated by an independant element :

- its characteristics are set forth in the static load-crushing law;
- a unilateral constraint is imposed between this element and the pipe.

The field of displacements is determined by the minimization of the energy under imposed constraints. The Frank and Wolf algorithm [5] is used ; it is an extension of the simplex method. There is also a good agreement between calculation (table IV and figures 6,7) and tests.

5. CONCLUSION

The calculations presented justify the method used to obtain impact loads : calculation with a beam model and simulation of the impact with the help of a local nonlinear stiffness. Although the plastic hinge model is over-simplified, it provides a conservative value of impact loads. Finite element results are much more precise. Moreover, it is to be noted that the static test results, as introduced into the calculational models, are sufficient to obtain a realistic estimation of impact loads.

REFERENCES

[1] C. CAUQUELIN - P. CAUMETTE - J.L. GARCIA - E. SERMET
"Experimental studies of PWR primary piping under LOCA conditions" - SMIRT 5 - Paper F 6/1.

[2] P. CAUMETTE - P. CHOUARD - A. MARTIN
"Study of pipe rupture dynamics" - paper n° F 8/4, this conference

[3] A. HOFFMANN
"Système CEASEMT : programme TEDEL" - Report N. 1930 (CEA/SACLAY)

[4] A. HOFFMANN - A. MILLARD
"Brève description des méthodes de choc applicables au fouettement des tuyauteries - Programme TEDEL" - Report EMT/SMTS/BAMS 80/123 (CEA/SACLAY)

[5] A. COMBESCURE
"Appuis unilatéraux" - Report DEMT/SMTS/BAMS 80/35 (CEA/SACLAY)

Table I : Experimental results

Test	Whipping time (ms)	Vertical velocity at impact (m/s)	Kinetic energy at impact (kJ)	Maximum impact load (kN)	Time to obtain maximum load (ms)
1	10,52	32.	/	464.	1.
2	13.83	/	/	468.	1.05

Table II : results of plastic hinge method

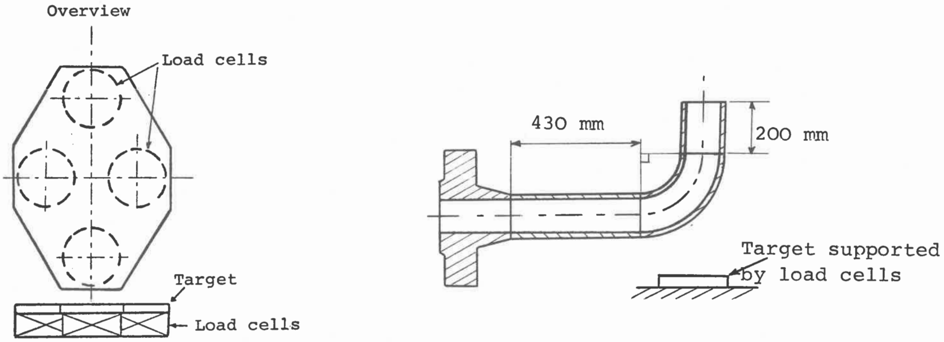
1	11.4	36.9	7.2	528.	1.
2	13.6	40.6	10.8	606.	1.

Table III : results of TEDEL code with a contact element

1	10.75	32.7	6.56	474.	1.05
2	13.14	39.	11.61	584.	1.

Table IV : results of TEDEL code with unilateral constraint

1	9.8	34.8	7.79	427.	1.
2	12.1	42.9	11.64	467.5	0.9



Side view
Target used to measure impact forces

Figure 1 Test section for pipe whip tests

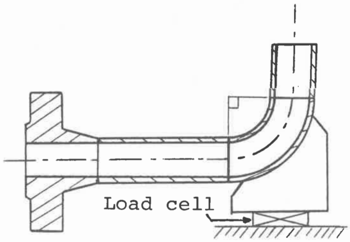


Figure 2 Test section for jet thrust measurement

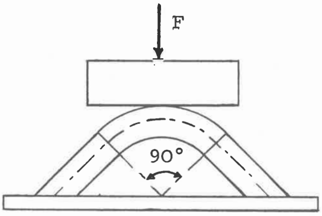


Figure 3 Test section for the static crush test

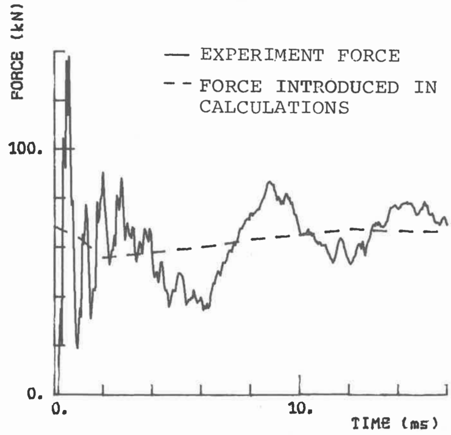


Figure 4 Jet thrust measurement

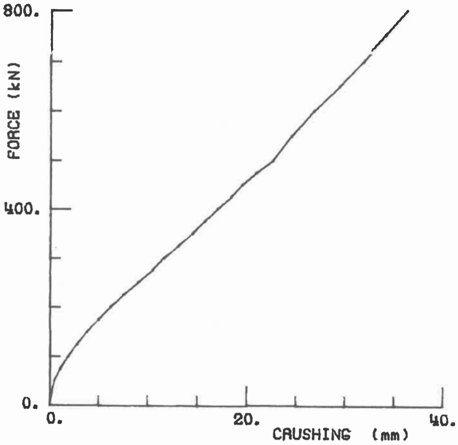


Figure 5 Applied force versus pipe crush relationship

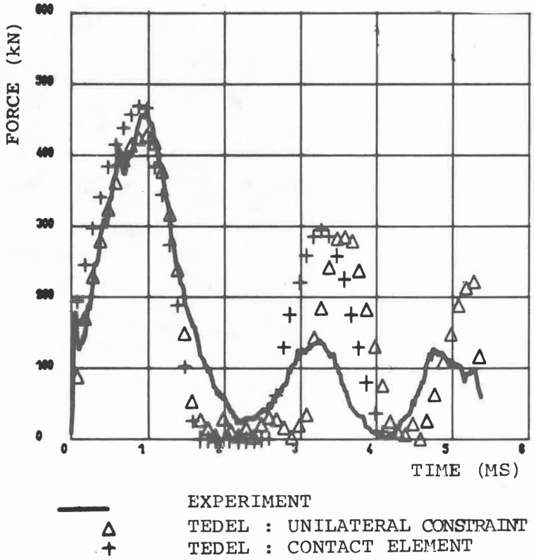


Figure 6 Calculated and experimental impact load (gap 0.180 m)

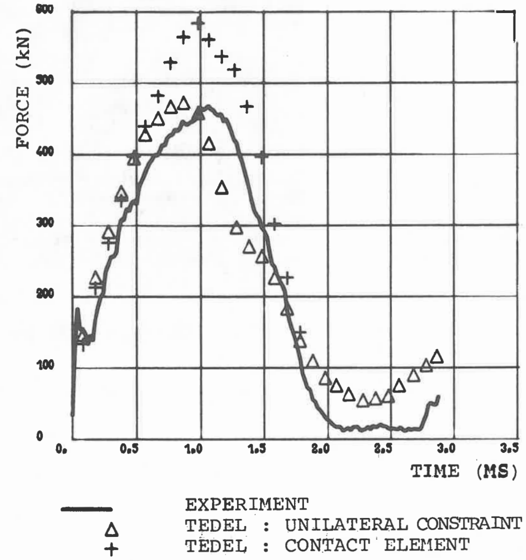
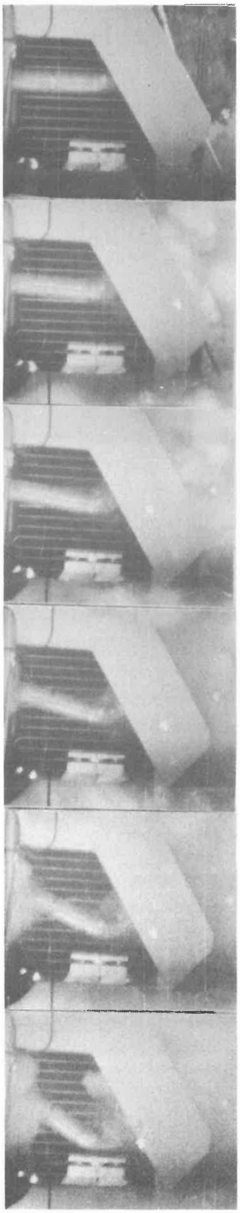


Figure 7 Calculated and experimental impact load (gap 0.270 m)



t = 0

t = 2.8 ms

t = 4.7 ms

t = 6.5 ms

t = 8.4 ms

t = 10.3 ms

Figure 8 Pipe whip movement (gap.180 m)

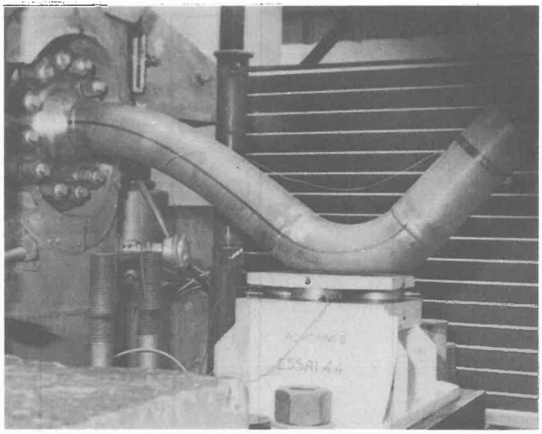


Figure 9 Pipe after test (gap 0.180 m)

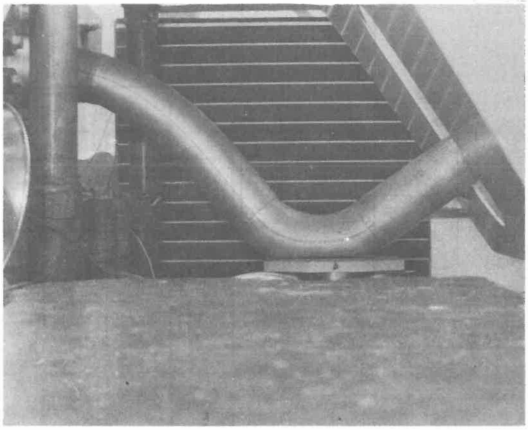


Figure 10 Pipe after test (gap 0.270 m)