Experimental Studies of Pipe Impact on Rigid Restraints and Concrete Slabs

J.L. Garcia, P. Chouard, E. Sermet
Commissariat à l'Energie Atomique, C.E.N. Cadarache, B.P. No. 1, F-13115 St Paul-lez-Durance, France

SUMMARY

In order to estimate the effects of pipe impacts on supporting structures and concrete barriers, the ELECTRIC POWER RESEARCH INSTITUTE, has financed, with the participation of FRAMATOME and COMMISSARIAT A L'ENERGIE ATOMIQUE, an experimental program performed at Cadarache Research Center. Its objectives are :

- to measure impact force exerted by a whipping pipe on an elastic compression restraint,
- to determine the degree of damage which occurs during pipe impact on a concrete slab.

This program includes sixteen tests. Experimental conditions are : pressure 16.5 Mpa, temperature 315°C. Test sections are 3 inch schedule 80 piping made of carbon steel similar to A106 grad B.

Two types of tests have been performed :

a) eleven tests with impact of the pipe on a rigid structure. The impact force is measured and the pipe whip is recorded with a high speed camera (5000 frames per second). The different parameters of the study are :
   - the location of impact on the pipe : elbow or straight part of the pipe
   - the initial gap between the pipe and the restraint.
   - geometrical characteristics of the test section such as : pipe thickness, elbow radius, length of the terminal part of the pipe between the breach and the elbow.

The analysis of one test has been achieved with a finite element code, TEDEL, from the CEA system. These dynamic elastoplastic calculations are based on a beam formulation, the impact is simulated by a local non linear stiffness which represents the local resistance curve of the pipe. This stiffness is obtained from a crushing test on a simplified geometry. Calculation results are compared to experimental data.

b) five tests with impact on a concrete slab. The target is simply supported around its perimeter by load cells. The pipe and the initial gap are the same for all the tests. The parameters are the thickness and the mechanical characteristics of the slab (compressive strength of the concrete, reinforcement).
   For the first test, the overal structural response of the target is calculated.

This analysis is divided in two parts :

- determination of the impact force assuming the target is rigid (same analysis as for previous tests with impact on rigid restraint but the local crushing stiffness is calculated with a shell code)
- calculation of the response of the slab under this input force.

INTRODUCTION

In the evaluation of pipe rupture consequences on a power plant it is necessary to take into account forces exerted by whipping pipes on surrounding structures. The ELECTRIC POWER RESEARCH INSTITUTE, the COMMISSARIAT A L'ENERGIE ATOMIQUE and FRAMATOME have jointly funded an experimental program to study pipe impacts. This program began at the end of 1981 at Cadarache research center, it will be achieved in 1983. Tests are presented hereafter as well as two analyses performed by the COMMISSARIAT A L'ENERGIE ATOMIQUE.

1. EXPERIMENTAL PROGRAM

This program is performed at the AQUITAINE facility |1|. Test sections are 3" schedule 80 or 10 pipes made of steel equivalent to A106 grade B. Experimental pressure and temperature are : $p \simeq 2400$ psi , $T \simeq 600°F$. Pipe breaks are initiated with an explosive cord (breach opening time lower than one millisecond). This program is divided in two parts :

- tests with impact on a very stiff structure made of steel,
- tests with impact on a concrete slab.

1.1 - Tests with impact on stiff stucture :

The purpose of these tests is to measure the impact load exerted by a whipping pipe. The target structure is equipped with load cells.

The parameters of the study are the geometry of the pipe, the initial gap between the pipe and the target, and the location of the impact on the pipe : straight part or elbow. A typical test section is presented in figures 1a-b. Different values of parameters are summarized in table 1. The main measurements are :

- pressure and temperature in the vessel and in the pipe,
- pipe displacement with a high-speed camera (5000 frames per second),
- reactions on vessel supports,
- impact load on the target structure.

Presently nine tests have been carried out. One can observe that pipe deformation depends on the geometry of the whipping pipe :

- for test sections with a short vertical pipe, plastic strain is localized at a small distance from the elbow see figure 1-b
- for test section with a long vertical pipe, plastic strain is more uniformly distributed along the pipe length.

Concerning impact one can notice that :

- the maximum force was recorded during test 5 (see in table 1) : the force applied to the target increases up to 385 kN in 0.8 ms; the corresponding pipe crushing being 12.6% with respect to the outside diameter;
- when impact takes place in the straight part of the pipe, the subsequent plastic strain develops mainly at the support level.

1.2 - Tests with impact on a concrete slab

These tests are directed to study the behavior of a concrete slab when impacted by a whipping pipe. The slab is simply supported at its edges, the geometry of the pipe and the gap between the pipe and the slab are the same for all the tests (see figure 2a-b). The parameters of the study are the geometrical and mechanical characteristics of the slab. Values of these parameters are given for two tests in table 2.

Main measurements are :

- pipe displacement with a high speed camera (figure 3),
- strain gauges on slab rebars,
- forces on slab supports.

The main results of the first test are given hereafter. Pipe velocity at impact is estimated through the movie scrutiny to v = 55 m/s.

The observed effects of pipe impact on the concrete slab are :

- local effect : very slight penetration of the pipe (about 1 mm) ,
- overal effect : the residual deformation of the slab is estimated to 7 mm,
- the maximum strain measured by strain gauges on rebars during impact does not exceed 0.3% (figure 4).

2. ANALYTICAL STUDIES

One test of each type has been calculated with the finite element code TEDEL from CEASEMT system |2|.

2.1 - Test with impact on a rigid structure

Test 5 (see table 1) is analyzed. The calculations use a beam formulation and impact is simulated by a local non linear stiffness. This methodology previously gave consistent results compared to experimental data |3|,|4|. The main assumptions of this analysis are as follows :

- loading : the jet reaction applied to the pipe during the depressurization is measured in test 1 (table 1) with a similar test section but without any gap between the pipe and the support,
- mechanical characteristics of the pipe : previous analyses |3| related to pipe whip tests performed with austenitic stainless steel pipes showed that influence of strain rates on mechanical characteristics could be neglected in pipe whip calculations. Static characteristics have then been used, in the present analysis, although material is different. This point is discussed hereafter
- local crushing stiffness of the pipe : contrary to pipe whip, strain rates are very large in the impact zone and so greatly influence this crushing stiffness. However a good estimation of this stiffness may be obtained through a static crushing test at room temperature if the dynamic mechanical characteristics for experimental temperature are closed to the static characteristics at room temperature |4|. This condition is satisfied for the tested steel (see table 3). An experimental measurement of the stiffness is entered into calculation (see test section for crushing test and experimental result on figures 5a-b)

Comparison between calculation results and experimental data are presented in table 4 and figures 6a-b.

One can observe that the calculated pipe whip is too fast (pipe whip duration about 16% shorter than experimental one) and impact load is overestimated by about 21%.

In fact the maximum plastic strain measured on the pipe is not localized at the same place as it is according to calculation (figure 6-b). This discrepancy may be due to the use of static mechanical characteristics. Even if the mean value of the strain rate is not very high in the pipe, for ferritic steel it is perhaps not quite justified to neglect dynamic effects when the geometry of the pipe is such that a plastic hinge appears during pipe whip. Complementary calculations are presently being done to take into account strain rates.

2.2 - Test with impact on concrete slab

As the deformation of the slab during impact is not very significant, impact and slab deformations are calculated separately :

- calculation of pipe whip and impact with TEDEL code assuming the slab is perfectly rigid,
- calculation of the deformation of the slab loaded by the calculated impact force and the jet thrust after impact.

2.2.1 - Calculation of impact force

The calculation is similar to the one presented before. However the impact zone is different; due to the large gap, the pipe rotation is important and the impact takes place in the elbow mid-point. The local crushing stiffness of the pipe is then different.The experimental result used before is not valid for this analysis.

For the present analysis the estimation of the local stiffness is obtained through an elastic-plastic calculation with a shell code TRICO from CEASEMT system |2|. The modeling of the structure is presented in figure 7. Dynamic characteristics at 300 °C are entered into calculations in order to satisfy experimental conditions of impact.

The calculation of pipe whip and impact is similar to the one presented §2.1. Main results are given in table 5 and figure 8.

The calculated pipe deformation is quite different from the previous calculation, the plastic deformation is uniformly distributed along the pipe length due to the inertia of the vertical pipe. This last result is in good agreement with the experimentally observed pipe behavior confirming that TEDEL calculations predict the two different modes of deformation obtained according to the test section geometry |5|.

2.2.2 - Calculation of reaction on slab supports

Presently the analysis of the slab behavior is performed as follows :

- modeling of the slab as an oscillator,
  - . The equivalent mass is calculated using, for the slab field of displacement, shape functions compatible with support conditions. This equivalent mass is found equal to a quarter of the full mass of the slab.
  - . The eigen value entered into calculations is experimentally obtained by analyzing the records of the reactions on the slab supports.
- the input force is the impact force calculated by TEDEL code and the subsequent jet thrust.

Comparison between the calculated and the measured reactions on the supports is given in figure 9.

R E F E R E N C E S

|1| "Study of pipe rupture dynamics - AQUITAINE II program".
Paper F8/4 - SMIRT 6 - Paris
P. CAUMETTE - Ph. CHOUARD - A. MARTIN

|2| "The CEASEMT FINITE ELEMENT SYSTEM" - COMMISSARIAT A L'ENERGIE ATOMIQUE - DIVISION D'ETUDE ET DE DEVELOPPEMENT DES REACTEURS Département des études mécaniques et thermiques.

|3| "Study of pipe whip and impact"
Paper F8/6 - SMIRT 6 - Paris
J.L. GARCIA - A. MARTIN

|4| "A simplified methodology for calculations of pipe impacts : comparison with tests"
ASME 1982 - Winter Annual Meeting (Phoenix - USA)
J.L. GARCIA - A. MARTIN - Ph. CHOUARD

|5| "Mechanical effects of breaks on PWR primary pipings-analytical interpretation of test"
Paper F1/4 - SMIRT 7 - CHICAGO
A. DUPUY - A. MARTIN - J.P. THOMAS - J.L. GARCIA - P. CAUMETTE - Ph. CHOUARD

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Table 1 : Parameters in impact tests on stiff structure

Test	L_1 (feet)	δ_1 (Inches)	α (feet)	L_2 (inches)	Observations
1	12	0	0	8	Pipe size 3" schedule 80
2	12	0	4	8	" " "
3	12	2	0	8	" " "
4	12	2	4	8	" " "
5	12	8	0	8	" " "
6	12	8	4	8	" " "
7	12	8	0	8	Pipe size 3" schedule 10
8	12	8	4	8	" " "
9	12	8	0	14	Pipe size 3" schedule 80 Elbow R/D = 3
10	12	2	0	72	Pipe size 3" schedule 80
11	12	2	4	72	" " "

Table 2 : Characteristics of the slab

Test	Slab thickness	Concrete compressive strength at 28 days (MPa)	Percent reinforcement (kg/m^3)
1	6"	60.5	150
2	3"	44.8	150

Table 3 : Steel mechanical characteristics for the elbow

Experimental conditions	Yield strength (Mpa)	Maximum stress (MPa)	Ultimate strain (%)
Static 20°C	290	445	36.8
Dynamic 300°C	220	400	31

Table 4 : Comparison between calculation and experimental results

a) Pipe whip

Test	Calculation			
Pipe whip duration t_e (ms)	Pipe whip duration t_c (ms)	Vertical impact velocity (m/s)	Kinetic Energy at impact (kJ)	$\frac{t_e - t_c}{t_e}$ (%)
10	8.4	41	9.4	16

b) Impact

	Test	Calculation
Maximum impact force (kN)	$F_e = 385$	$F_c = 466$
Time to obtain maximum impact force (ms)	0.8	1.1

$$\frac{F_c - F_e}{F_e} = 21\ \%$$

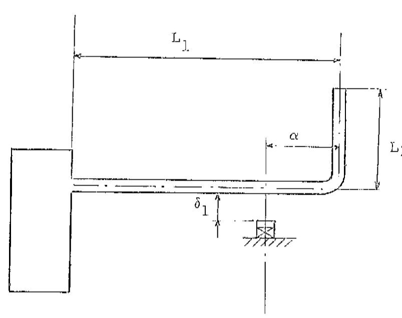
Table 5 : Calculation results

a) Pipe whip

Test	Calculation			
Pipe whip duration t_e (ms)	Pipe whip duration t_c (ms)	Vertical impact velocity (m/s)	Kinetic Energy at impact (kJ)	$\frac{t_e - t_c}{t_e}$ (%)
69	56.7	60.	85.8	18

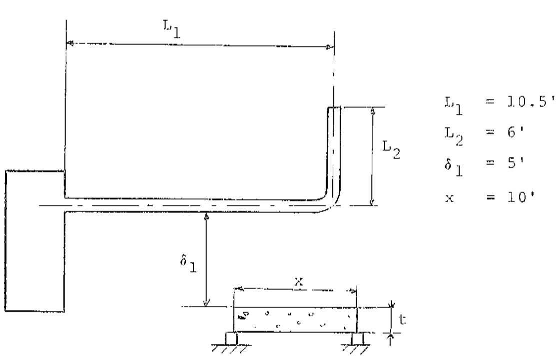
b) Impact

Maximum impact force (kN)	8 49
Time to obtain maximum impact force (ms)	2.5

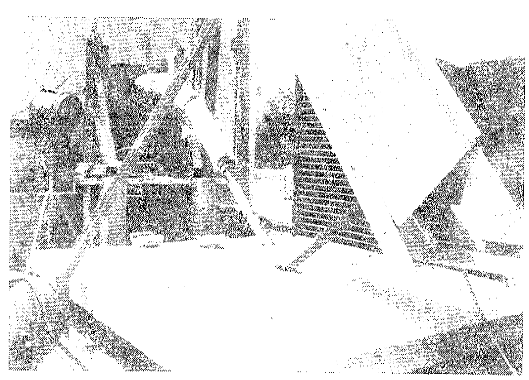


1-a Schema of a test section (impact on a stiff structure)

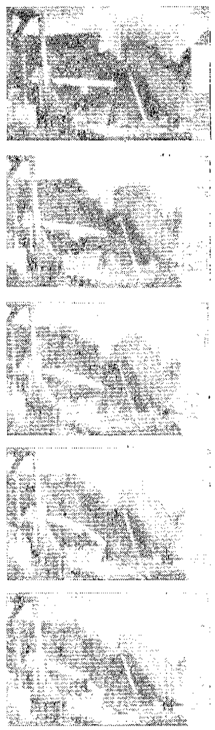
1-b Pipe after test (impact on a stiff structure)



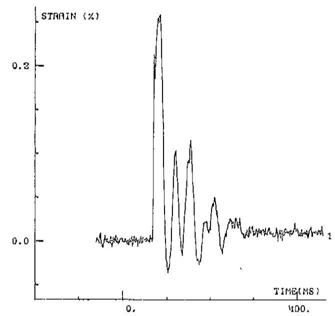
2-a Schema of a test section (impact on a concrete slab)



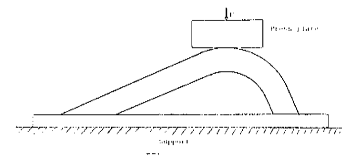
2-b Pipe after test (impact on a concrete slab)



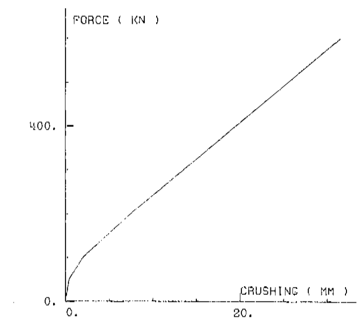
3 Pipe whip movement (impact on a concrete slab)



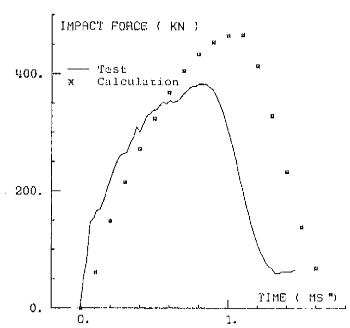
4 Strain on rebar



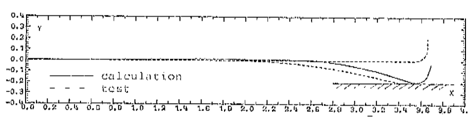
5-a Test section for static crushing test



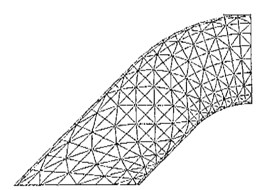
5-b Applied load versus crushing



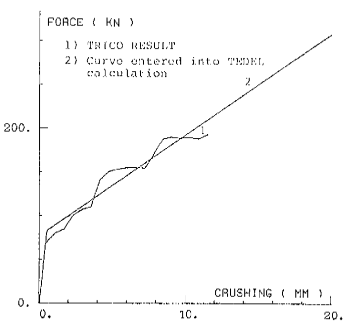
6-a Impact force



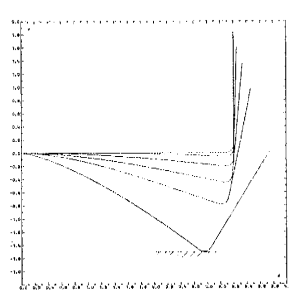
6-b Pipe deformation



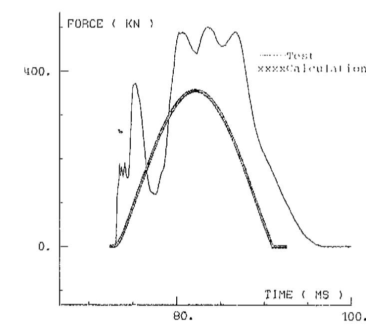
7-a Modeling of the elbow for shell calculation



7-b Calculated relationship between applied load and pipe crushing



8 Pipe deformation at different steps of calculation



9 Reaction on slab supports