AN ANALYSIS OF THE DYNAMIC ELASTO-PLASTIC BEHAVIOUR OF A PIPE DURING THE PIPE WHIP ACCIDENT

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SUMMARY

The pipe whip phenomenon consequent to a loss of coolant accident is studied by an ad hoc method and computer program.

The following situation is studied: a pipe is accelerated by the fluid ejected after a LOCA and hits a restraint, located at a given distance from the pipe.

The pipe is schematized by means of a series of lumped masses connected by springs; each spring and mass may be different from the others; each spring can have either an elastic or plastic behaviour depending on the value of the applied loads, elastic unloading after plastic loading can be dealt with. The restraints are located at a given distance and act only after the pipe has travelled such an amount; an elastoplastic approach (with elastic unloading) is followed in this case, too.

The applied LOCA load can be specified in a stepwise method. A direct step-by-step Euler-Gauss integration method is used (different integration procedures could be anyway incorporated quite easily).

An evaluation of the pipe and restraints load capability is given on the basis of data published in the open literature on allowable strains in bars during dynamic loading and on instability moments on pipes.

Typical cases are presented in which the pipe and restraints deformations are followed before, during and after the impact; the oscillating phase after maximum restraint deformation can be followed introducing appropriate damping.

The program automatically gives displacements, moments and kinematics characteristics on a given temporary basis, maximum values and a comparison with the allowable values.

Typical cases are presented, some peculiar characteristics of this phenomenon are shown, the influence of the various parameters (restraint gaps, pipe vincular conditions, applied force values, etc.) is discussed.

The authors decided to make the effort of studying such a problem, because they considered the current methods of analysis (with which comparisons are provided) as generally unsatisfactory and could not find anything similar in the open literature.

1. Introduction

The full and sudden severance of one of the major pipes inside the container of a nuclear power station is an event, which has to be taken into consideration in order to assess a satisfactory safety degree of the plant.

Consequence of such an event are:

a) the loss of coolant through the break, with a correspondent severe transitory for components inside the reactor (which is mitigated through the use of Emergency core cooling systems)
b) the possibility of uncontrolled movements of a pipe accelerated by the outcoming fluid with consequent further damage either to the containment itself or to other surrounding pipes. The second event consequences may be mitigated through the use of appropriate restraints, whose scope is to prevent the pipe from excessive and uncontrolled movements, potentially dangerous for other components.

Briefly the situation studied in the present paper is the one illustrated in fig. 1: let us assume that a sudden breakage occurs at location 1, the pipe will be accelerated by the outcoming fluid and will eventually impact the restraint R, which will be elongated in order to absorbe the energy given by the travelling jet and not completely absorbed by the pipe itself.

The simplest model one can think of, is to assume a rigid behaviour of the pipe and a rotation around a supposed hinge at station n. 2; from that a simple energy balance yields:

$$F_J \cdot \theta \cdot l_{12} = \int_0^\theta F_r \cdot l_r \, d\theta$$

where obviously

F_J = applied jet force

θ = pipe rotation

l_{12} = distance from force application point to hinge

l_r = distance from restraint to hinge

F_r = applied restraint force

Really against such a model a lot of criticism can be forwarded, namely it neglects:

a) pipe flexibility between stations 1 and 2 and between stations 2 and 3
b) pipe inertial forces
c) exact hinge location and dissipation of energy in the pipe through plastic rotations
d) rebound phoenomena
e) elasto-plastic deformation of the pipe during loading and unloading.

For this reason it was made the effort of writing the 'ad hoc' program FRUSTA

5 to account for the effects, which cannot be considered in the simple model.

2. Analytical model

2.1 - Pipe model

The pipe is modelled by a serie of masses connected by means of massles springs, having non linear characteristics; the mass of the pipe is accordingly lumped in a number of nodes, whose number is the result of a compromise between accuracy and computation time (maximum 30).

The rigidity of the connection springs is a function of the applied moment, while shear is neglected due to the slenderness of the structure. However as an incremental approach is followed in order to compute deflections, forces and kynematic characteristics, the actual stiffness matrix K , function of applied load), may be approximated by the use of the tangent stiffness matrix K_t and a linear analysis may be performed for each step (of course the tangent matrix will change from step to step; besides as the stiffness characteristics for each element is different during loading and unloading, the total stiffness matrix will take into account this loading unloading effect.

The moment-curvature relationship for the pipe is obtained assuming that:

a) no ovalization in the pipe cross section exists
b) the material behaves, in the plastic range, according to the law $\sigma = A\varepsilon^m$ and in the elastic range according to $\sigma = E\varepsilon$
c) plane sections remain plane
d) deformations are due to moment only
e) the material behaves elastically during unloading or if the moment absolute value is less than a value M^*
f) M^* is equal to a predetermined value $\bar{M}$ during the first loading; after an unloading, M is equal to the value of the moment, for which unloading occurred (M_A) (see fig. 2)
g) in each element (spring) loadings and unloadings are defined on an "average" basis i.e. the whole element will be considered to load or to unload according to its medium point behaviour or to some other averaging device based upon energy.

2.2 - Restraint model

The restraint action is schematized in fig. 3, so if

- the displacement is less than X_E no action from the restraint
- if the displacement X is $X_G \leq X \leq X_E$ the restraint rigidity is FKO
- if the displacement X is $X > X_E$ the restraint rigidity is FK1
- during unloading the restraint rigidity is FKO
- if loading occurs after an unloading the stiffness is FKO, provided that $F \leq F^*$ (see fig.3)
- no negative force can be given by the restraint.

Consequently for each restraint the parameters are X_E, X_G, FKO, FK1

2.3 - Geometrical configuration

The program can deal with a straight pipe, either as a cantilever, or as a pipe fixed at the ends with a hinge applied in the point of assumed breadage (see fig.4 a,b).

As each element can be defined in a separate way, end conditions different from fixity can be considered; a dummy element with proper rigidity and length can accomodate for different support conditions.

However, with reference to fig.1, the part between stations 0 and 2 (assumed break location at station 1) is directly modelled either statically and dynamically, the 2-3 part can be considered only as a support condition (see paragraph 3 for an example).

2.4 - Jet forces

The jet forces can be introduced in a stepwise manner; no discussion is here given of the magnitude and time dependence of such loads, which can be, at least approximately, found in the open literature, see [1] , as an example.

2.5 - Integration procedure

The motion equations are numerically integrated by means of a step by step procedure; the "constant average acceleration" procedure was selected, because it is the one, for which, instability problems should not be very important.

With reference to the general equations:

$$|\dot{u}_1| = |\dot{u}_0| + (1-\lambda)\,\Delta t\,|\ddot{u}_0| + \lambda\,\Delta t\,|\ddot{u}_1|$$

$$|u_1| = |u_0| + \Delta t\,|\dot{u}_0| + (0.5-\beta)\,\Delta t^2\,|\ddot{u}_0| + \beta\,\Delta t^2\,|\ddot{u}_1|$$

where

$|\ |$ denotes a vector

u displacement

$\dot{u}$ velocity

$\ddot{u}$ acceleration

Δt time interval

and subscripts 0 and 1 denote the values at the beginning and at the end of the interval, the used method is the one for which:

$$\lambda = 1/2 \qquad \beta = 1/4$$

2.6 - Allowable strain on pipe

The allowable strain on the pipe is due to section instability consequent to large ovalization phoenomena. This value has been derived from the following formula:

$$\varepsilon = a \times \frac{t}{R}\, 0.6\, \gamma$$

where

a = safety factor (assumed 0.9)
t/R= thickness over radius ratio
γ = gradient factor

The 'gradient factor' is introduced in order to account for the difference of strain in the section during bending as suggested by Gerard [2] ; suggested values are in the range (1.2÷2.0) [3,4] .

3. Typical results

In order to show two typical cases of application of the code and to see the influence of various parameters, two typical situation were selected.

3.1 - Case A

This case occurs in a typical BW reactor situation, the main steam line is considered and a break is assumed to occur at the connection between pipe and vessel; with reference to fig. 5 a break is assumed to occur at location 0, the outcoming fluid thrust will act on the pipe as a rightwards force aplied at location 0. Five restraint are located in the 1-2 span in order to prevent excessive pipe deformation; an initial clearance between pipe and restraint is considered (XE in fig.2). The model is presented in fig. 6; the pipe is modelled by means of 11 elements; elements n.2-11 model the 1-2 span while element n. 1 is a dummy element introduced in order to account for the flexibility of the 2-3-4 span.

The pipe (completed by water and insulation) mass is lumped in the eleven nodes; node 11 takes into account the influence of the elbow at the top of the pipe.

Ten cases were run in order to have an idea od the influence of the various parameters on the strains in the pipe and in the restraints.

Case number 1 is the reference one, and the characteristics are listed below:

materials property:

$E = 2.1\times10^{10}$ Kg/m^2
$m = 0.20$
$A = 7.2\times10^{7}$ Kg/m^2

pipe properties

Element	Length (m)	Radius (m)	Thickness (m)	Notes
1	2.7	0.293	0.0162	dummy element
2	2.8	0.293	0.0243	
3-10	1.2	0.293	0.0243	
11	1.2	0.293	0.0243	elbow mass added

Restraint properties

Location	XE(m)	XE(m)	FKO(kg/m)	FK1(kg/m)
2	0.15	0.1515	2.9×10^7	1.3×10^5
4	0.15	0.1515	2.9×10^7	1.3×10^5
6	0.15	0.1515	2.9×10^7	1.3×10^5
8	0.15	0.1515	2.9×10^7	1.3×10^5
10	0.15	0.1515	2.6×10^8	1.16×10^6

Thrust characteristics
(see fig. 7)

time (msecs)	force (kg)
2.66	1.73×10^7
95.20	1.20×10^5
-	6.50×10^4

For the other cases the data are the same, with the exceptions listed below:

Case 2 : For all the restraints the initial clearance is halved
XG = 0.075 XE = 0.0765

Case 3 : No clearance on the restraints

Case 4 : Overhang length (l_{11}) doubled

Case 5 : Overhang length halved

Case 6 : Restraint 10 rigidity (FKO and FK1) halved

Case 7 : Restraint 10 rigid

Case 8 : Without dummy element 1, pipe fixed at the end rigidities of restraint 10 halved (as case 6)

Case 9 : Similar to case 6 but for thrust forces, equal to roughly 2/3 of the reference case

Case 10: Restraints clearance halved, non elastic period on the restraint 10 (XE=XG)

The case were run till inversion of the velocity of node 11 was reached.

In the following table the main results are listed:

The allowable moment (correspondent to a critical maximum deformation of 7.6%) is 3.39×10^5 Kgm and is overcome in cases 4 and 7.

In fig. 8 the displacement of the nodes for case 1 and 6 are presented at the various times.

3.2 - Case B

This case occurs in a typical BW reactor situation in the 2-3 span in fig. 5; relief valves are located there and it is assumed that one of the connection sweepolettes fails and a jet is generated with a consequent downwards thrust load. The model is presented in fig. 6b, the pipe is modelled by means of 9 elements (from 2 to 10), number 1 element is a dummy element provided to account for the elasticity of 1-2 span; the elasticity of 3-4 span was not taken into consideration.

The pipe, as well as relief valves, mass is lumped in the nodes.

Restraints number 2 and 5 simulate the presence of structural beams, which could act as supplementary restraint units.

The jets is applied at node 4, which is considered to behave as a hinge, as a consequence of the failure of the pipe.

The applied forces are shown in fig. 7b.

F_1 = 320t t_1 = 6 msec

F_2 = 215t t_2 = 19 msec

F_3 = 176t t_3 = 74 msec

F_4 = 230t

The cases were run till inversion of the velocity is obtained on node 4.

Four cases were run, with the same material property as far case A.

Case number 1 is the reference case and its data are listed below:

pipe properties

Element	Length (m)	Radius (m)	Thickness (m)	Notes
1	0.17	0.293	3×10^{-4}	Dummy element
2	0.70	0.293	0.0243	
3	0.40	0.293	0.0243	
4	0.90	0.293	0.0243	
5	0.60	0.293	0.0243	
6	0.33	0.293	0.0243	
7	1.10	0.293	0.0243	
8	1.50	0.293	0.0243	

9	1.70	0.293	0.0243
10	1.50	0.293	0.0245

Restraint properties

Location	XG(m)	XE(m)	FKO(kg/m)	FK1(kg/m)
2	0.28	—	1×10^{8}	—
3	0.15	0.1515	$1.16\times10^{+8}$	5.2×10^{5}
5	0.28	—	1×10^{8}	—
6	0.144	0.1155	1.16×10^{8}	5.2×10^{5}
8	0.144	0.1155	2.32×10^{8}	1.04×10^{6}

For the other cases the data are the same with the exceptions listed below:

case 2 : dummy element 1 rigidity reduced to simulate a hinge

case 3 : the pipe is built in at 1 station

case 4 : overhang length element 5 is increased by 0.15 m.

In the following table B all the main data are listed.

The allowable moment for the pipe is the same as for case A, and is overcome in case number 3.

In fig. 9 typical displacement profile at various times are presented.

4. Conclusions

Two typical situations were studied: a "long cantilever pipe" case as in case A and a "short double fixed pipe" as in case B. Different parameters influence can be derived from a comparison between the different runs in the two set of cases.

For cases A the following conclusion can be drawn:

a) the main parameters are the overhang length and the initial clearance as can be seen from the differences in pipe moment and restraint strain among runs 1,4,5 and 1,2,3. An increase in overhang length causes an increase in the pipe moment as it would be expected (see fig.10); similary an increase in the initial clearance tends to cause higher loads either on the pipe and on the restraint (see fig.11).

b) There exists an optimum for the restraint rigidity as can see from the comparison of cases 1,6,7 (see fig.12); too high a rigidity tends to produce excessive loads on the pipe, while if it is too low, restraints resistance demand could to be too strong.

c) The influence of the end condition (see runs 6 and 8) is neglibible.

For cases B, at the contrary, the main parameter seems to be the end condition at 1 location, as one can see from the comparison of cases B1,B2, B3; in this case too there exist an optimum of rigidity (case 1), where either the pipe moments and the restraint loads are acceptable.

In conclusion it is clear that the various parameters (overhang length, clearance, end conditions, etc) influence can be quite different in different geometrical situations; a relatively sophisticated model like the one used is felt to be necessary in order to obtain a correct dimensioning of the restraints, what cannot be made by simple models.

References

[1] Moody "Prediction blowdown thrust and jets forces" ASME paper 69-HT-31 (1969)

[2] Gerard "Handbook of structural stability-part III - Buckling of curved plates and shells" NACA-TN-3738

[3] Donnel "A new theory for the buckling of thin cylinders under axial compression and bending" Trans. ASME vol 56 n. 11 Nov. 1934

[4] Flügge "Die stabilität der Kreiszylinderschale" Ing. Archiv. Bd 3, 1932

[5] Dini Lazzeri "Descrizione del programma di calcolo FRUSTA" to be published by CNEN.

TABLE A

Case	Impact time (msecs)	Maximum moment on the pipe (kgm)		Displacement (max) of node 10-11 (m)		Maximum force and strain on the restraint (kg)			Notes
		loc.	value			restr.	force	strain	
A1	22.90	10	$3.26x10^5$	0.18	0.30	10	$5.24x10^5$	3%	
A2	15.56	10	$2.98x10^5$	0.09	0.17	10	$5.16x10^5$	1.5%	
A3	many impacts on all restr.	10	$2.18x10^5$	0.02	0.02	10	$3.306x10^5$	0%	
A4	27.70	10	$3.618x10^5$	0.16	1.31	10	$5.14x10^5$	1%	overcoming of limit moment
A5	23.20	10	$2.31x10^5$	0.19	0.22	10	$4.35x10^5$	4%	
A6	22.90	10	$2.46x10^5$	0.30	0.41	10	$2.79x10^5$	17%	
A7	22.90	10	$3.65x10^5$	0.15	0.28	10	$2.21x10^6$	8%	four impacts on 10 restr.
A8	22.90	10	$2.49x10^5$	0.28	0.40	10	$2.84x10^5$	16%	
A9	31.70	10	$1.98x10^5$	0.20	0.26	10	$2.43x10^5$	6%	
A10	15.80 28.60	10	$2.3\ x10^5$	0.32	0.46	8 10	$5\ x\ 10^4$ $2.85x10^5$	--	

TABLE B

Case	Impact time (msecs)	Maximum moment on the pipe (kgm)		Displacement (max) of node 4 (m)	Maximum force and strain on the restraint (kg)			Notes
		loc.	value		restr.	Kg	%	
B1	17 28	0	$3.19x10^5$	0.30	6 3	$2.41x10^5$ $1.76x10^5$	4.6 1.0	--
B2	16.7 22 28.6	5	$3.50x10^5$	0.35	6 3 5	$2.6x10^5$ $1.9x10^5$ $9.9x10^5$	5 3 -	--
B3	21 24.4	1	$4.77x10^5$	0.25	6 3	$1.98x10^5$ $1.81x10^5$	1 1	--
B4	18 27	0	$3.34x10^5$	0.31	6 3	$2.20x10^5$ $1.70x10^5$	5 1.5	--

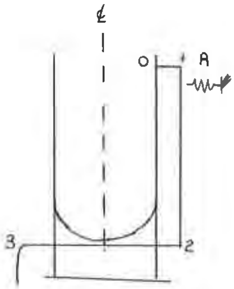


fig.1 - General layout

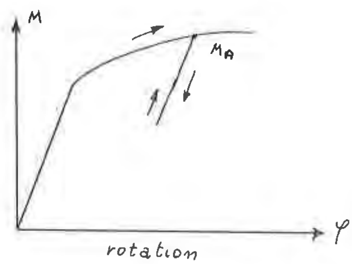


fig. 2 - Momento rotation relationship for elements

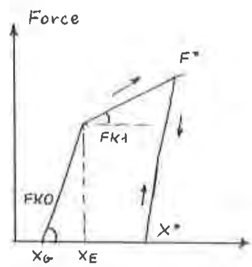


fig.3 - Force displacement relationship for restraints

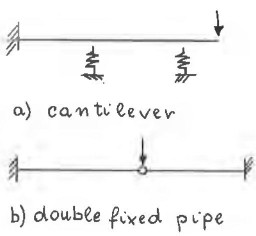


fig.4 - General scheme

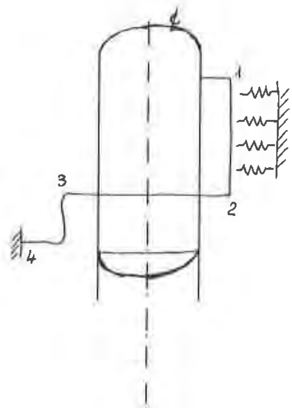


fig.5 - General scheme for piping

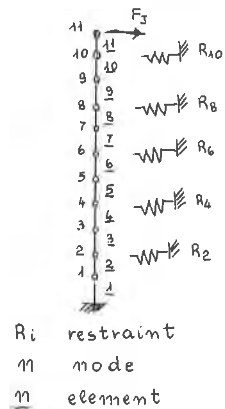


fig.6A - Scheme for cases A

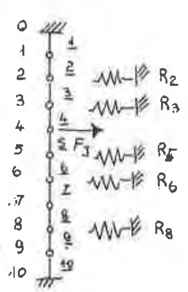


fig.6b - Scheme for cases B

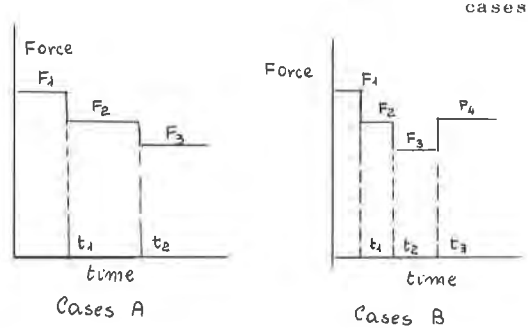
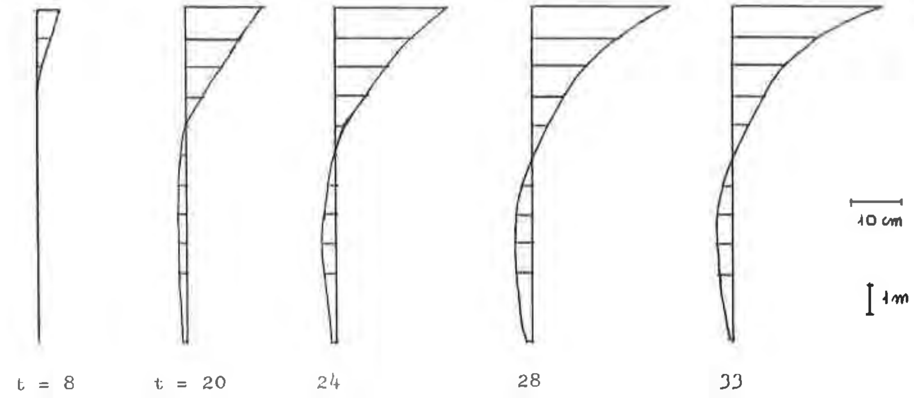
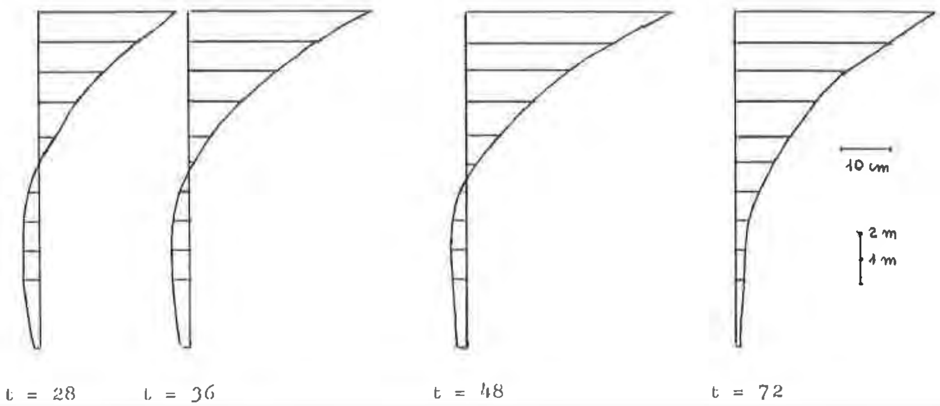


fig.7 - Time-thrust curves



Case A_1



Case A_6

fig.8 - Displacements of the pipe at various times after beginning of the jet (Cases A)

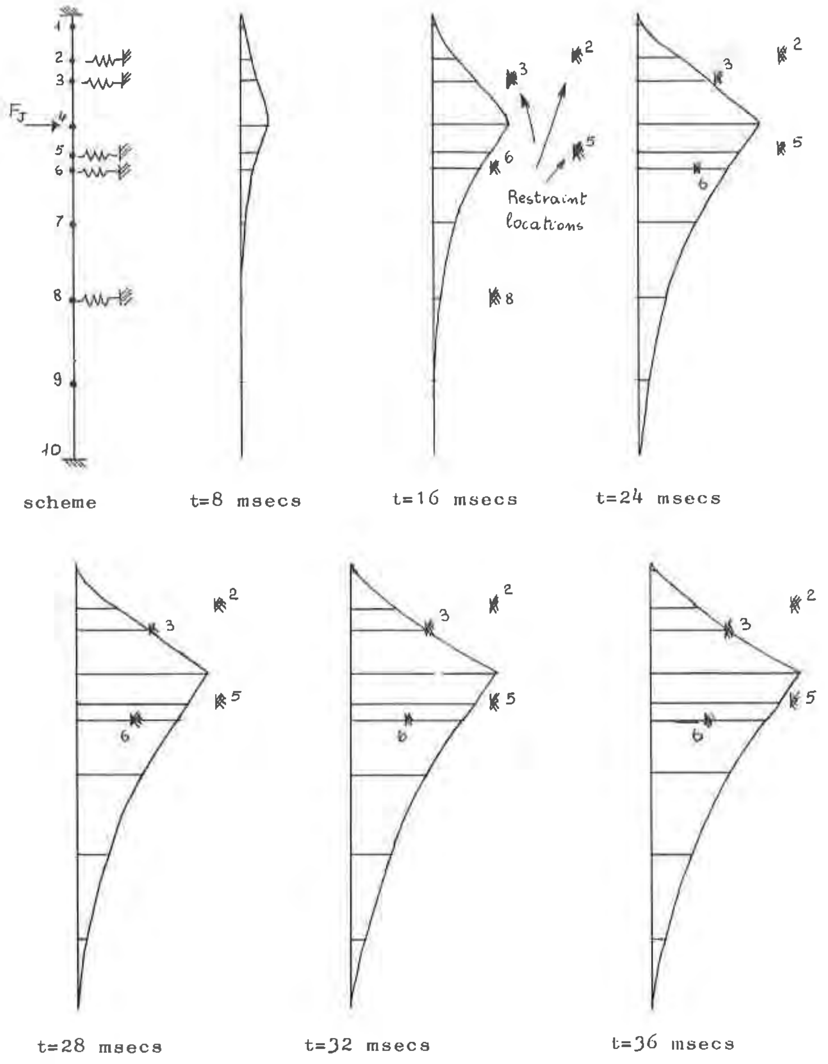


fig. 9 - Displacement of the pipe at various time (case 1b)

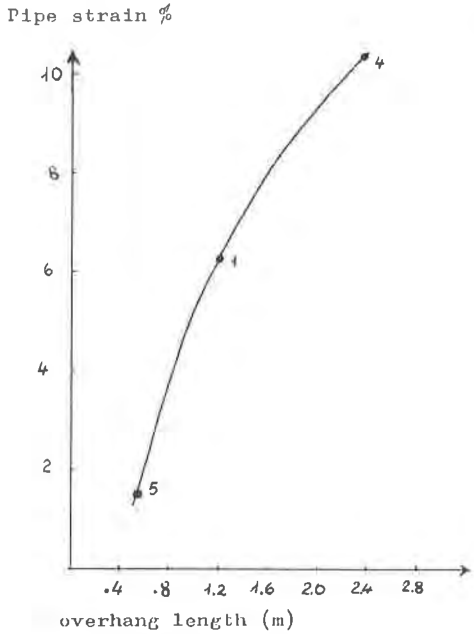


fig.10 - Influence of overhang length on pipe strain (cases A)

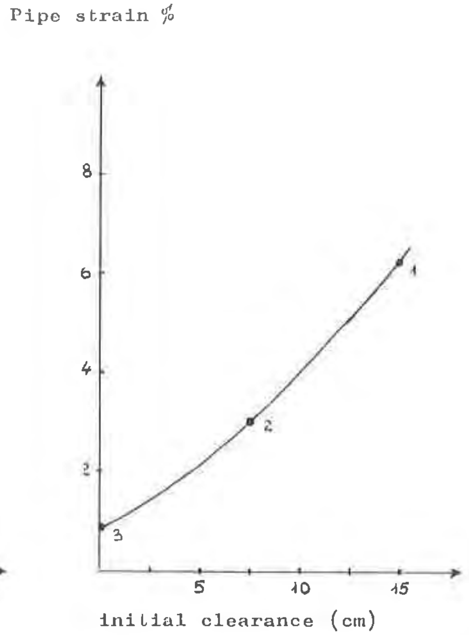


fig.11 - Influence of initial clearance on pipe strain (cases A)

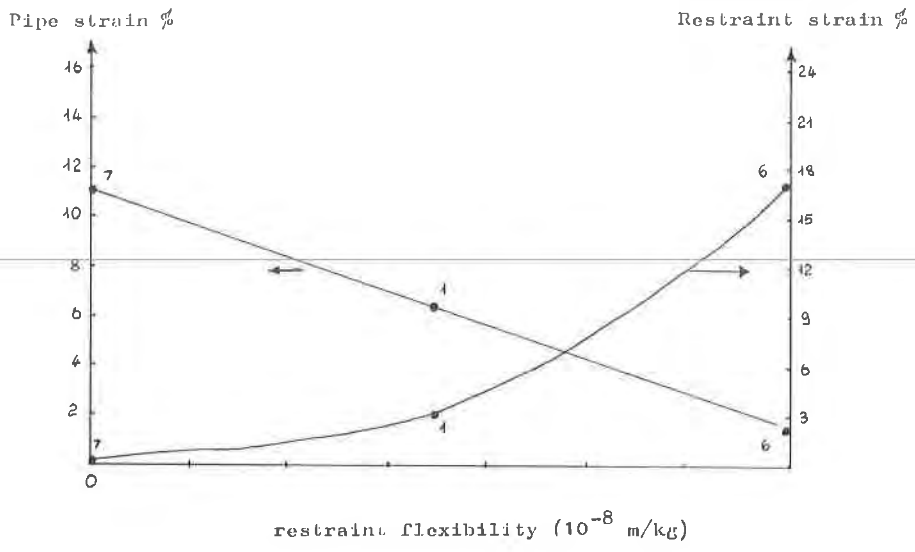


fig. 12 - Influence of restraint flexibility (Cases A)