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- PIPE WHIP ANALYSIS USING THE TEDEL CODE

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1. INTRODUCTION

In view of their abundance, piping systems are one of the main components in power industries and in particular in nuclear power plants. They must be designed for normal as well as faulted conditions, for safety requirements. For example, in case of a sudden break, the pipe whip must be studied in order to determine if the free pipe may damage neighbouring structures like other pipes, concrete containments, etc... The prediction of the dynamic behaviour of the free pipe requires accounting for several non-linearities. For this purpose, a beam type finite element program (TEDEL) has been used. The aim of this paper is to enlight the main features of this program, when applied to pipe whip analysis. An example of application to a real case will also be presented.

2. MAIN FEATURES OF PIPE WHIP ANALYSIS

Piping systems are rather flexible structures. This is mainly due to the presence of pipe bends, where the cross-section tends to ovalize. This deformation is accompanied by higher stresses across the thickness of the pipe. In case of an instantaneous circumferential guillotine break, the pipe becomes free to move and the fluid which was initially at a high pressure will communicate its energy to the pipe. This is most of the time depicted by the introduction of a following jet force, applied at the free end of the pipe. As a consequence, the piping system will undergo very large displacements, which will be amplified by the developments of plastic hinges along the pipe, due to the high level of the stresses, in particular in elbows. Therefore, the main non-linearities which must be accounted for in a pipe whip analysis are the following :

- Geometric non-linearity, due to the large displacements. Indeed it handles of large translations and rotations, but strains can be supposed to remain small with a reasonnable accuracy. (12 Charakter per 25.4 mm).
- Material non-linearity, since the stresses will overstep the yield stress. The spread of the plastic zones across a given cross-section will result in a plastic hinge, in the usual sense of strength of materials.
- Following jet force, which remains tangent to the pipe. Such a load is non-conservative and introduces an additional non-linearity.
- Unilateral contact, when the pipe impacts another component. Indeed, the non-penetration condition for the two surfaces in contact must be written in the form of an inequality. Moreover, it may be necessary to introduce some non-linear stiffness at the contact, to account for local crusch rigidities.

A typical configuration for the pipe whip analysis is shown on Figure 1.

It is important to note that all these features must be modelled in the analysis since they have a strong influence on the impact forces which are the desired results.

From a theoretical point of view, the complete problem is much complex since the only data are the initial conditions (state of stresses and pressure in the pipe) and the duration of the guillotine break at some given location.

Consequently the fluid and the structure behaviour should be determined on a fully coupled basis, meaning that the relevant equations should be solved simultaneously. The solution is not so easy since there are different characteristic periods in the problem. It is being developped in a fast dynamics computer code PLEXUS [1] [3] of the CEASEMT System [2].

However, as a first approximation, it has been chosen to uncouple the hydraulic and the structural problems. As a result , for the whip analysis, it is possible either to use local information, i.e. the fields of pressure, fluid velocities and densities, or to use global information, i.e. the jet force. The choice of one or the other solution may depend on the geometry of the piping system.

From a computational point of view, the use of tridimensionnal shell finite elements would lead to a prohibitive cost. Consequently, it is necessary to use a beam-type finite element program, which will supply the global behaviour of the pipe.

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3. GENERAL PRESENTATION OF THE TEDEL PROGRAM [8][9]

TEDEL is a general purpose finite element program of the CEASEMT System, specially oriented towards the calculation of tridimensionnal structures made of beams or pipes. The main elements are two nodes beams and pipes, and three-nodes flat shell elements. Some special elements are available for piping analysis (see Figure 2):

- curved elbow element,
- mitred elbow,
- T junction,
- tubes bundle element,
- contact element,
- coaxial tubes, with a sheet of water,
- elements with a sudden broadening or shrinking of the cross section, for fluid-structure interactions.

The nodes may have six or eight degrees of freedom, which are the three translations, the three rotations and for the fluid discretisation, the pressure p and an axiliary variable π which obeys the following equation :

$$-p = \frac{d^2\pi}{dt^2}$$

Following the classical concepts of usual strength of materials, the dual variables are generalized stresses, which are the classical axial and shear forces, bending moements and torque.

For the material behaviour, calculations may be performed in elasticity, plasticity with isotropic or kinemactic strain-hardening, or creep with any law for the creep rate according to the user's choice :

$$\frac{d\epsilon^*}{dt} = f(\sigma^*, \epsilon^*, T, t \ldots)$$

Where ϵ^* is an equivalent plastic strain, σ^* is an equivalent stress, and T the temperature. Besides, a special attention has been given to the modelisation of reinforced concrete behaviour laws : a model has been derived to account for the cracks in the concrete and the plastic deformation of the reinforcements, as well as for cyclic effects (unloading and reloading) [5][6][7] (see Figure 3).

A large variety of loads may be applied to the structure :

- nodal forces,
- weight (including the weight of the fluid)
- inner pressure,
- uniform rotation,
- distributed loads,
- acceleration,
- thermal loads,
- local pressure variation (for the fluid).

Concerning the boundary conditions, displacements can be prescribed at some nodes ; equalities as well as inequalities can be written between degrees of freedom. For fluid-structure interactions, some given pressure or flow can be prescribed at a node.

Various types of analysis are possible using the TEDEL program :

. Static analysis, either with a linear or a non linear material, and assuming small or large displacements. Moreover, it is possible to calculate the EULER's critical load in the frame of the usual elastic stability theory, or to determine an elastoplastic critical load by using some displacement monitoring strategy to compute the response of the structure [10].

. Dynamic analysis - either in the elastic linear domain : modal analysis ; response analysis by modal recombination ; seismic analysis by quadratic recombination of the various modal responses, including a correction for neglected modes, and the possibility of different spectra at different nodes ; influence of an initial state of stresses on the frequencies ; account for viscous damping.

- or in the non linear (material and/or geometric) domain, by direct integration, using a Newmark type algorithm.

An interesting feature of the TEDEL program is the possibility to calculate the fully coupled acoustico-mechanical behaviour of the pipe.

For example, phenomena like the forced vibrations of a pipe, induced by the flow, or the effects of a water hammer, may be investigated.

TEDEL can determine the frequencies of the pipe filled with water, including the fluid frequencies and the added mass effects, as well as the transfert functions at one point of the circuit due to some unit signal at another point.

Moreover, it is possible to compute the acoustico-mechanical response of the pipe to the various loads already mentioned, accounting for non linear phenomena like the cavitation, the growth of a gaz bubble, the burst of a safety membrane, the variation of sound celerity and fluid density, etc..., and for singularities due to geometries changes (see the various elements already mentioned). Therefore, with such a program, it is possible to treat in a fully coupled way, the very first milliseconds of the pipe whip as long as the acoustic effects are predominant in front of the convective terms for the fluid. Then, it is necessary to use a computer code like PLEXUS. Many of the possibilities of the TEDEL program have been validated by comparisons between calculations and either experimental or analytical solutions. Some of them are given in ref. [12].

4. SOLUTIONS ADOPTED FOR PIPE WHIP ANALYSIS

In order to treat the pipe whip problem at a reasonnable cost but with a sufficient accuracy, the following solutions have been adopted in the TEDEL program for the main problems already mentionned in § 2.

4.1 - Geometrical non linearity [17]

In case of large displacements, equilibrium must be written on the final configuration, which is a priori unknown. Starting from a configuration C_t where the Cauchy stresses σ_t are in equilibrium with loads F_t, one must find the displacements and stresses increments due to a load increment ΔF such as :

$$F_{t+\Delta t} = F_t + \Delta F$$

Equilibrium equation can be written as :

$$(1) \int_{V_t} B_t^T \sigma_t \, dV_t = F_t \text{ equilibrium on } C_t$$

$$(2) \int_{V_{t+\Delta t}} B_{t+\Delta t}^T \sigma_{t+\Delta t} \, dV_{t+\Delta t} = F_{t+\Delta t}$$

equilibrium on $C_{t+\Delta t}$ which is unknown.

Where B is the matrix giving the strains in terms of the displacements.

This second equation is solved by means of an updated Lagrangian technique. The equilibrium equations on $C_{t+\Delta t}$ are convected on C_t ; by substracting (1) we find :

$$(3) \int_{V_t} \left[B^T_{t+\Delta t}\, \sigma_{t+\Delta t}\, J_{t+\Delta t} - B^T_t\, \sigma_t \right] dV_t = \Delta F$$

where $J_{t+\Delta t} = \dfrac{dV_{t+\Delta t}}{dV_t}$

If π denotes the 2nd Piola-Kirchoff stress tensor, we have :

$$\sigma_t = \pi_t$$

Moreover, in the local axis of the element, we assume that :

$$\sigma_{t+\Delta t} \simeq \pi_{t+\Delta t} = \pi_t + \Delta\pi, \text{ which gives :}$$

$$(4) \int_{V_t} \left[B^T_{t+\Delta t}(\pi_t + \Delta\pi)\, J_{t+\Delta t} - B^T_t\, \pi_t \right] dV_t = \Delta F$$

Then, an incremental elastic stress strain law is assumed between the 2nd Piola-Kirchoff stress and the elastic part of the Green strain :

$$\Delta\pi = D.\Delta\epsilon^e$$

The usual finite element technique leads to the following equation, solved in an iterative way :

$$K_t\, \Delta q^{(n+1)} = \Delta F + \Delta F^{(n)}_{NL}$$

where K_t is the stiffness matrix calculated on C_t

ΔF_{NL} are corrective forces due to the non linear terms.

n is the iteration index.

Some quasi-Newton acceleration techniques are used to improve the convergence of this algorithm.

4.2 - Material non linearity

The first approach [16][14] consists in treating the cross section as a whole that is to consider if there is or not a plastic hinge at a node. For this purpose, it is necessary to define the yield surface in terms of the generalized stresses of the pipe. These are shown on Figure 4 and include the inner pressure. Of course, the choice of the yield surface is not unique, since it corresponds to some measure of the state of stresses in an average sens. In TEDEL, a mean of order 2 has been assumed, which gives :

$$f(\bar{\sigma}^*, \lambda) \leq 0, \text{ with :}$$

$$\sigma^* = \sqrt{\alpha_1^2 N^2 + \alpha_2^2 M_y^2 + \alpha_3^2 M_z^2 + \alpha_4^2 C^2 + \alpha_5^2 p^2}$$

λ are internal parameters, and α_i are coefficients. It must be understood, that with such an approach, the cross section is or is not plastic, while in reality, plasticity spreads continuously over the cross section. However, it is possible to adjust the values of the α_i coefficients, in order to decide when the plastic hinge is forming. For example, they may be determined on the basis of a limit analysis. Besides, the plastic flow is assumed to be given by the normality principle, associated with the above criterion. The corresponding strains are generalized strains, like relative length variation and curvatures variations.

It is possible to account for hardening effects through the λ parameters : Isotropic and kinematic hardenings have been implemented as follows :

$$\sqrt{\sum_{i=1}^{5} \alpha_i^2\, \sigma_i^2} \leq R(\lambda) \quad \text{isotropic}$$

$$\sqrt{\sum_{i=1}^{5} \alpha_i^2\, (\sigma_i - X_i)^2} \leq R \quad \text{kinematic}$$

where the σ_i are the various generalized stresses (N, M_y, M_z, C, p) and the X_i are the kinematic hardening variables. The evolution of these variables is assumed to be of the form :

$$dX_i = \beta(\sigma_i - X_i)\, d\lambda$$

which is of the classical PRAGER-ZIEGLER type.

A second approach [13][15] has been followed, in order to have a better representation of what happens in the elbows. Indeed, elbows are very flexible if compared whith straight parts and the ovalization of their cross section results in high hoop stresses due to bending moments. This is accounted for in the global method by means of an inertia-modification :

$I' = \dfrac{I}{k}$ where k is the well known flexibility factor. In TEDEL, the ASME formula has been adopted :

$$k = \frac{1.65}{\lambda} \text{ where } \begin{cases} \lambda = \dfrac{eR}{r^2} \\ e = \text{thickness of the pipe} \\ r = \text{mean radius of the pipe} \\ R = \text{bend radius} \end{cases}$$

and the yield criterion has been modified accordingly. However, for some applications like calculations of pipes with thermal transients inducing thermal gradients across the thickness, it is desirable to have an accurate description of the state of stresses in the pipe. For this purpose, a special pipe bend has been developped [15] : it is based on Fourier's series developments of the local ovalization displacements. Strains are calculated according to the classical Kirchoff-Love thin shell theory.

Assuming a plane state of stresses, stresses are calculated using the classical Prandtl-Reuss plasticity theory. Then, a condensation technic eliminates the local unknowns in terms of the classical global unknowns. Integrations over the element volume are performed numerically, using integration points which are regularly distributed over the cross-section (see Figure 5).

Using such elements, it is possible to follow the spread of plasticity over the cross-section, but it is more costly than the global method.

Therefore, for pipe whip analysis, the global method will be preferred.

4.3 - Following force

It is possible to introduce the force induced by the fluid in two ways :

- either by a nodal force, which is the jet force and which continuously follows the geometry of the pipe. In TEDEL, it has been treated in an explicit way, i.e. the following force at time $t + \Delta t$ is estimated with the geometry at time t. This approach is well fitted for small radius pipe bends, since the applied load is localized. Whereas in the case of large radius pipe bends, it is advisable to distribute the force induced by the fluid all along the bend, as done below.

- or by an internal dynamical pressure p_d which may vary in the various elements versus time :

$$p_d(t) = p(t) + \rho(t)\, v^2(t)$$

where ρ = density
p = pressure
v = fluid velocity

This pressure may be determined by a preliminary thermohydraulical calculation. In a fully coupled approach, such a calculation will be made together with the mechanical response calculation.

4.4 - Unilateral contact [18] [19]

The impact of the pipe on a rigid or another deformable structure may be written as an inequality on the nodal displacements :

$$Aq \geq C$$

In TEDEL, two approaches have been followed to tackle with these inequalities :

- the use of contact elements, which are activated when the inequalities are violated, and which work only in compression. The reaction force developped in the element is of course function of the penetration which is a priori unknown. The solution is found by iterations :

$$L.\,\Delta q^{(n+1)} = F_o + \Delta F + \Delta F_{NL}^{(n)} + \Delta F_{UC}^{(n)}$$

where L is an operator depending on the mass and stiffness matrices and the choosen algorithm.
F_o - depends on the initial conditions at time t
ΔF is the load increment
$\Delta F_{NL}^{(n)}$ are the corrective non linear forces
$\Delta F_{UC}^{(n)}$ are the additionnal corrective forces due to the contact elements.

It must be noted that the convergence of such an algorithm is sometimes difficult ! Therefore it may be advisable to use the following

The use of Lagrange's multipliers, which leads to a modification of the total potential energy :

$$\Omega' = \Omega + \lambda^t (Aq - C)$$

The impact forces are found to be :

$$F_i = A^t \lambda$$

The usual equilibrium equations supply the displacements q in terms of the multipliers λ. Therefore these may be determined by maximizing a quadratic form under constraints :

$$\underset{\lambda}{\mathrm{Max}} - \frac{1}{2} E_1 \lambda^2 + E_2 \lambda + E_3 \text{ with } \lambda \geq 0$$

This problem is solved using the FRANK-WOLFE algorithm [18], which is proved to converge in a finite number of steps.

The main advantage of this second approach is to be fully implicit, if the time integration scheme has been chosen so.

5. EXAMPLE OF APPLICATION

Pipe Whip tests have been performed by C.E.A. [20] in France in order to investigate the behaviour of PWR primary piping under LOCA conditions. Among them tests of impacts of whipping pipes on rigid targets have been calculated [21] [22]. The tested pipes were made of a straight part (430 mm) terminated by a small radius bend and a small straight part (see Figure 6).

The dimensions of the pipe were 3" schedule 80 S and the bend radius was 1.5 d.

Two gaps were investigated :
h = 180 mm and h = 270 mm.

The material was an austenitic stainless steel (AISI 316 L). Operating pressure and temperature were 16,5 MPa and 320°C.

The guillotine pipe break was initiated by a pyrotechnical device, with an opening time inferior to one millisecond.

In a first test, a support equipped with load cells was placed just below the elbow in order to measure the jet force. The result as well as the value introduced in the computation are shown on Figure 7.

During the impact tests, the impact force was measured by a similar device. For the calculations, a simple mesh has been used (see Figure 8).

A non-linear spring has been placed under the elbow in order to account for the local crush rigidity of the pipe at impact. The spring stiffness has been determined by means of a static compression test on a similar elbow (see Figure 9) The corresponding force-displacement curve is displayed on Figure 10.

Calculations were performed for the two different gaps. Figure 11 shows the predicted deformed geometries at impact. The comparison between measured and calculated impact load is displayed on Figure 12.

It must be noted that, in these calculations the influence of the strain rate on the material properties has not been accounted for. Obviously, this should be the case, in particular for the additional non linear spring. In TEDEL, it is possible to introduce a stress-strain curve depending on the strain-rate ; for example, one of the few laws available in litterature could be adopted :

$$\sigma_{dynamic}(\epsilon, \dot{\epsilon}) = \sigma_{static}(\epsilon) \times \left[1 + (\alpha \dot{\epsilon})^{\beta}\right]$$

6. CONCLUSION

The TEDEL program has proved to be efficient for calculations of the pipe whip. The global method for plasticity and the Lagrange multipliers technic for unilateral constraints enable rather cheap calculations, with sufficiently large steps. However, the program does not account for phenomena like the full coupling betwenn the fluid and the pipe, and an accurate description of the impacted zone. This will be treated by the PLEXUS program which is being developped.

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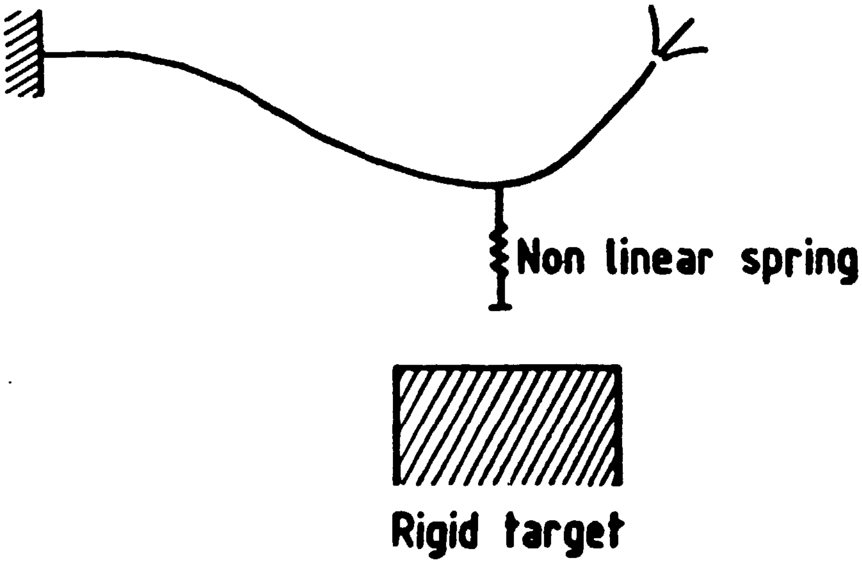


Fig. 1 - Display of whipping pipe with non linear crush stiffness

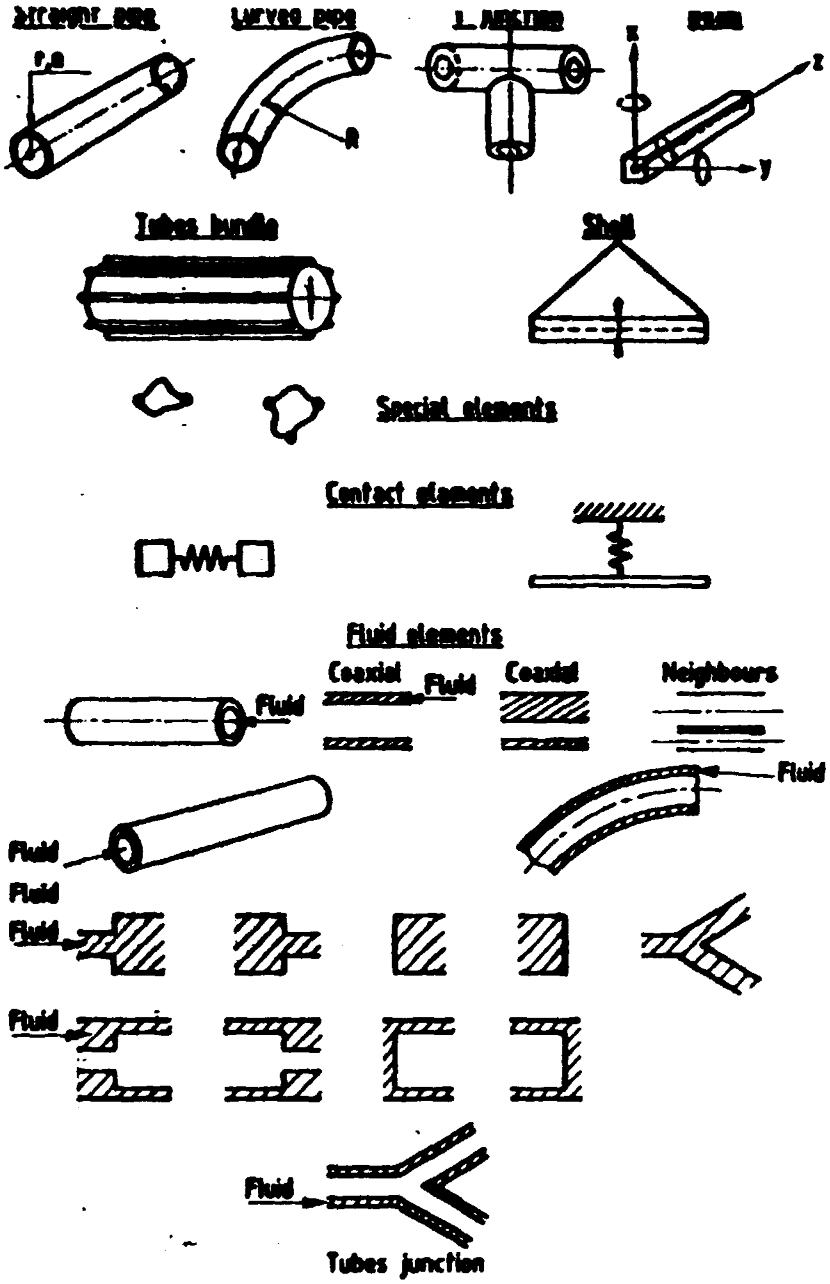
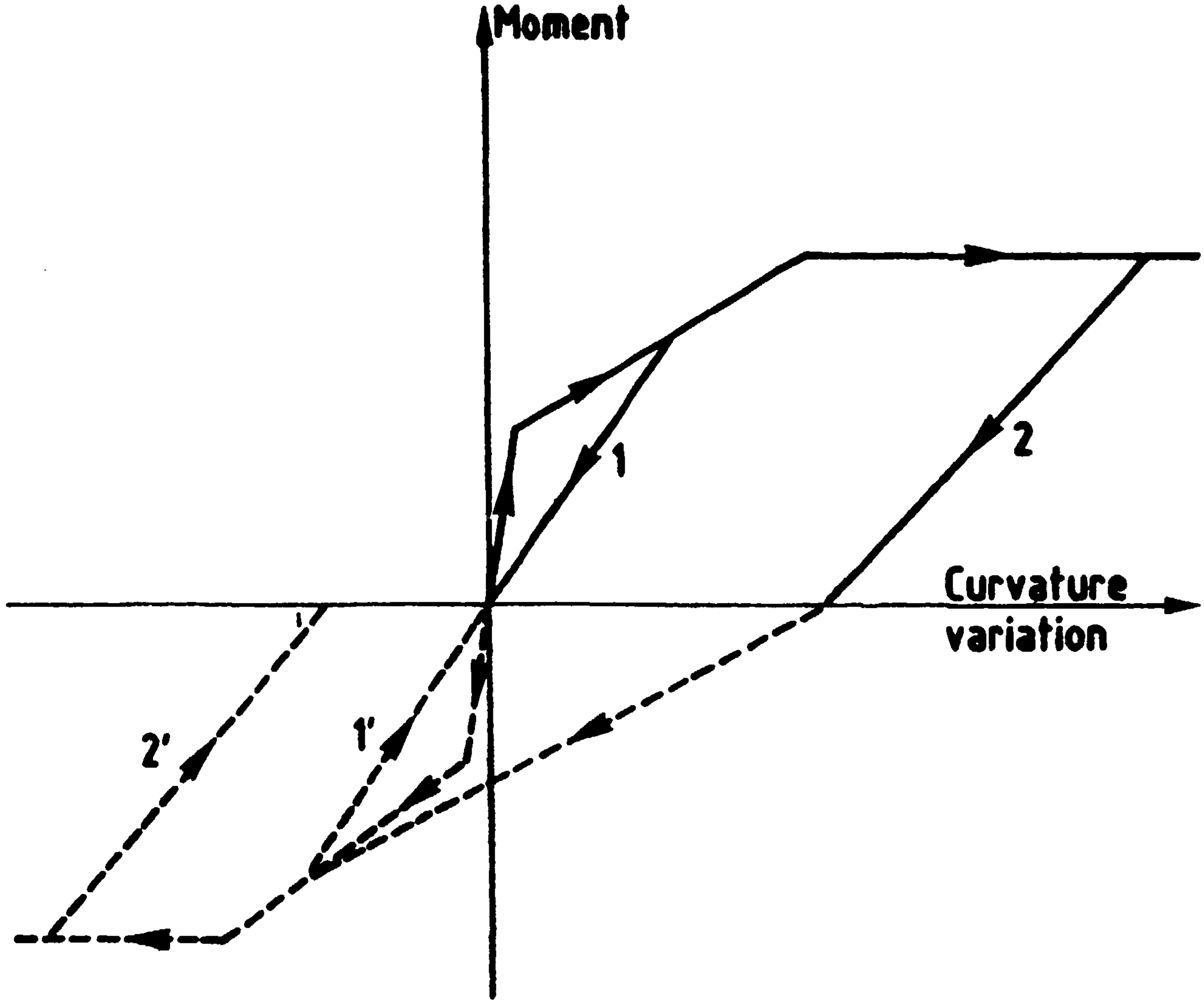


Fig. 2 - Tedel elements



1, 1' } Unloading at a moderate level

2, 2' } Unloading at a high level

Fig. 3 - Global behaviour law for reinforced concrete

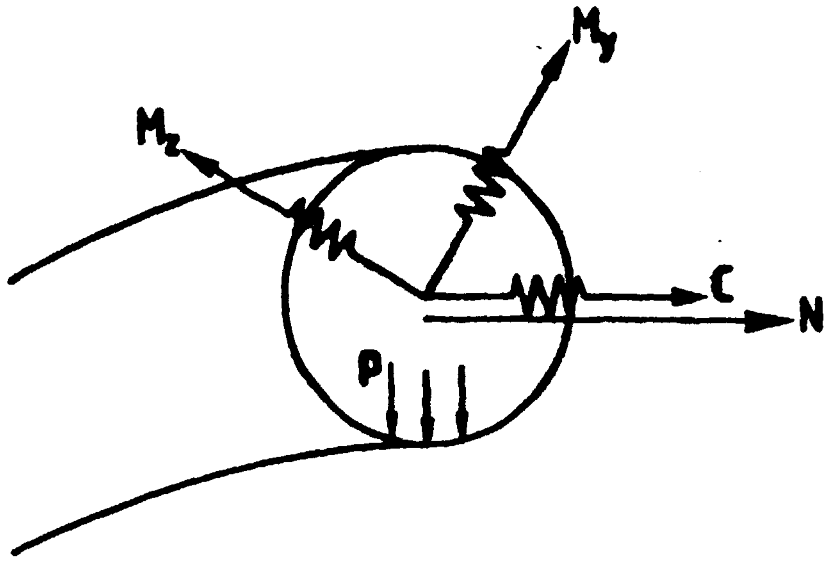


Fig. 4 - Generalized stresses for a pipe

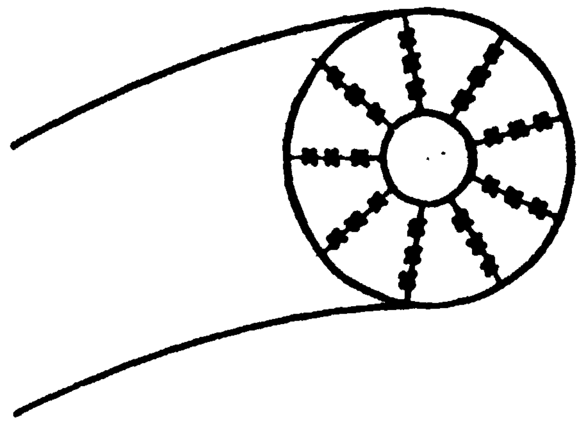
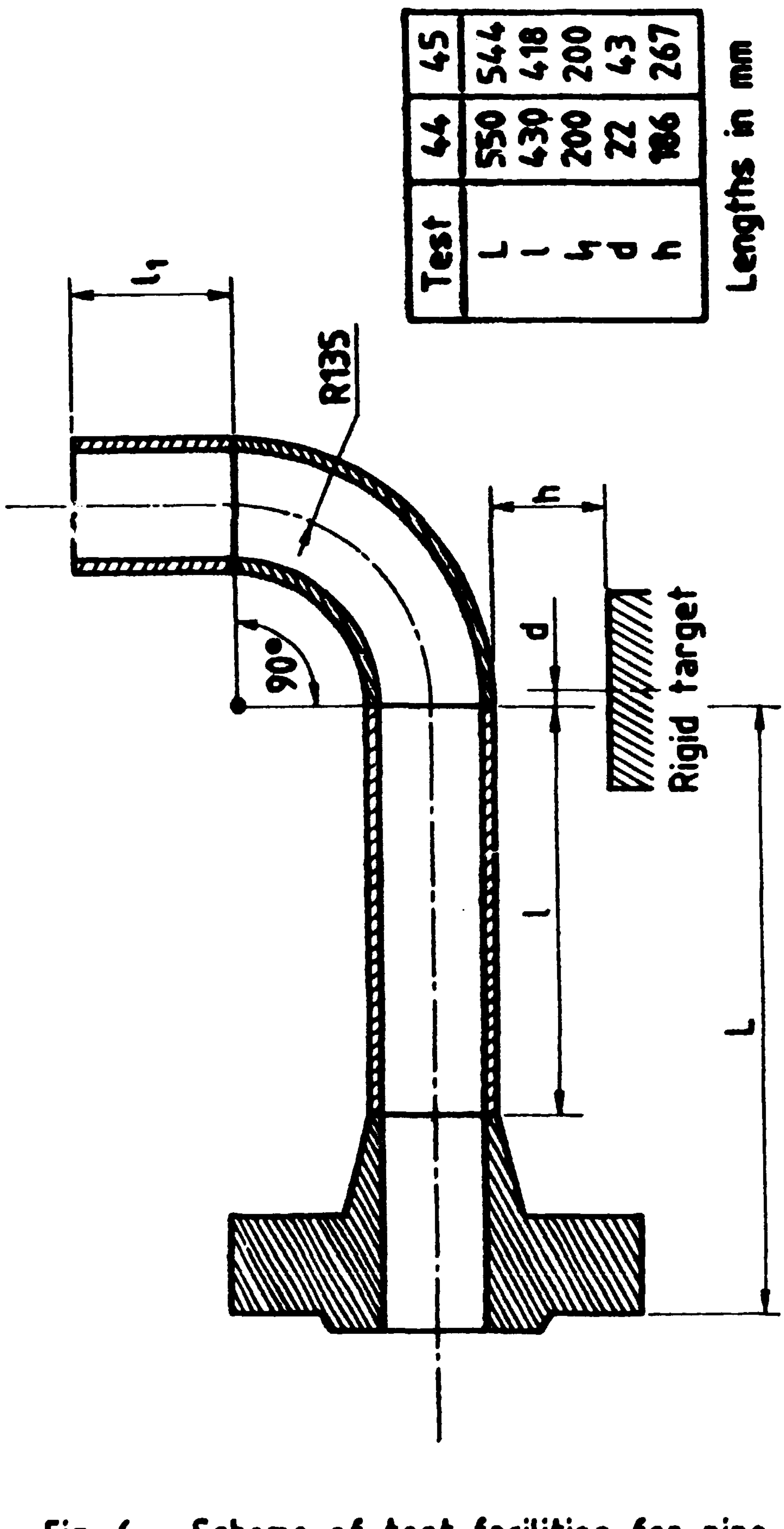


Fig. 5 - Integration points over the cross-section



Test	44	45
L	550	544
l	430	418
l_1	200	200
d	22	43
h	186	267

Lengths in mm

Fig. 6 - Scheme of test facilities for pipe whip

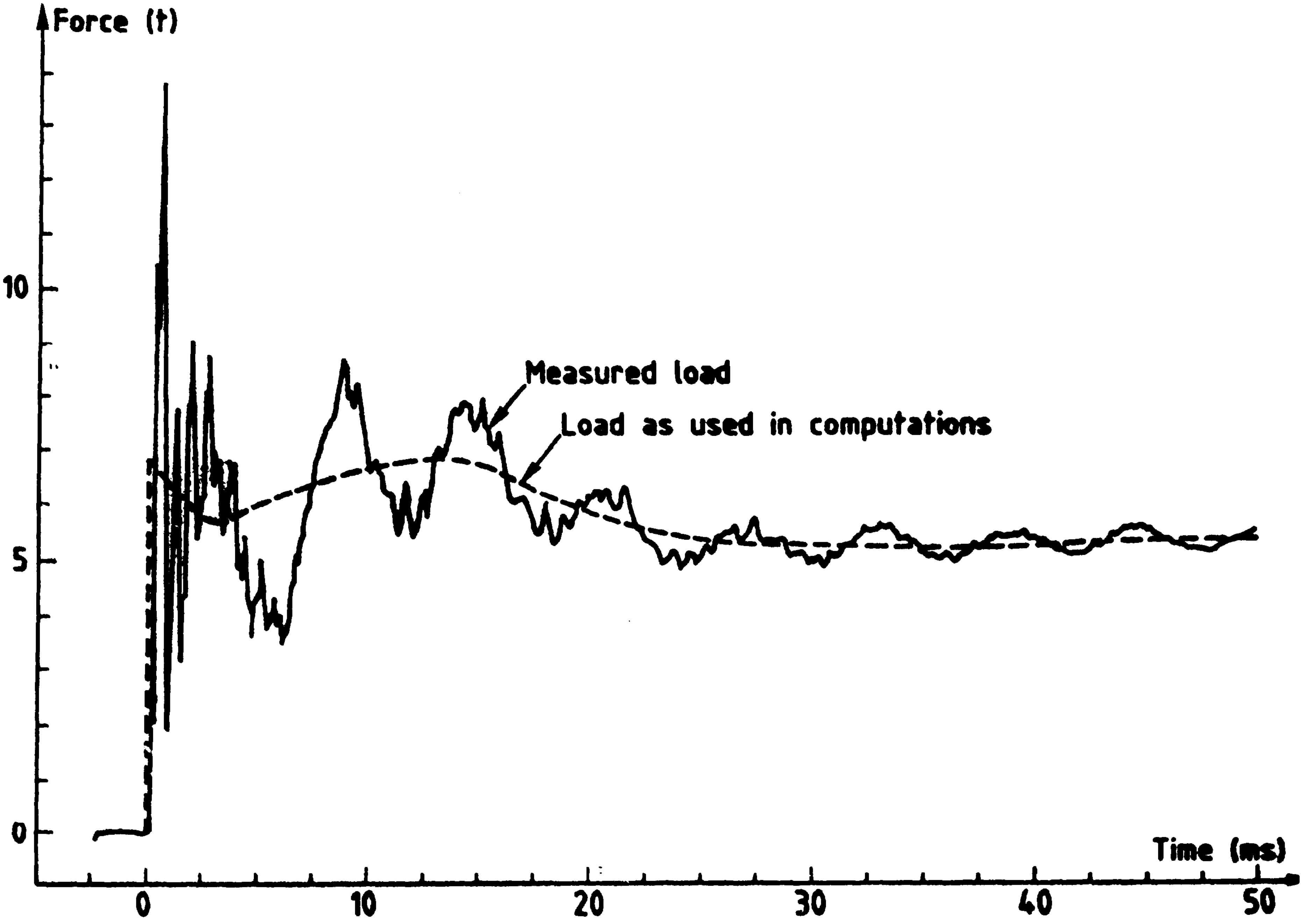


Fig. 7 - Measured following force

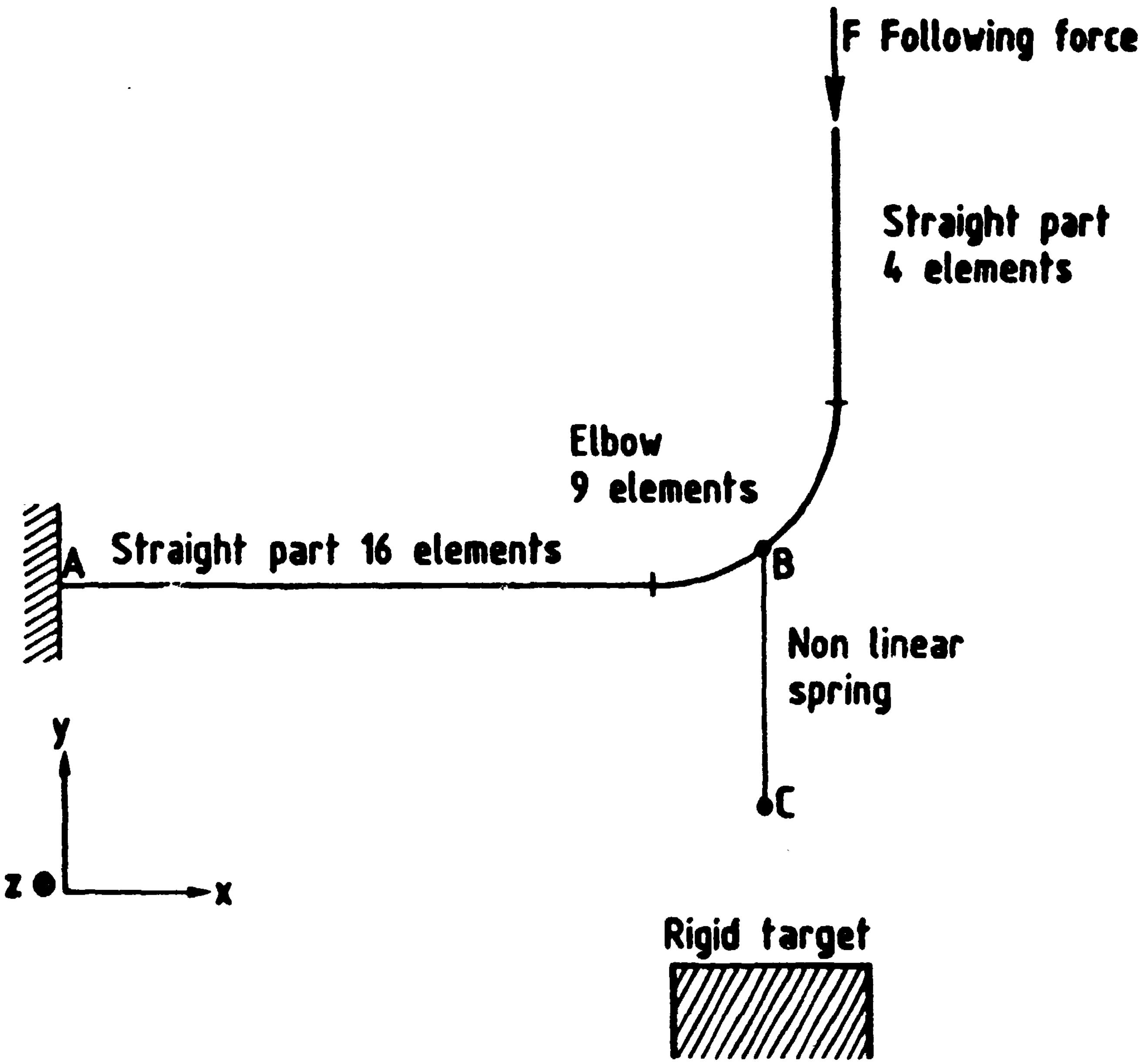


Fig. 8 - Model used for computations

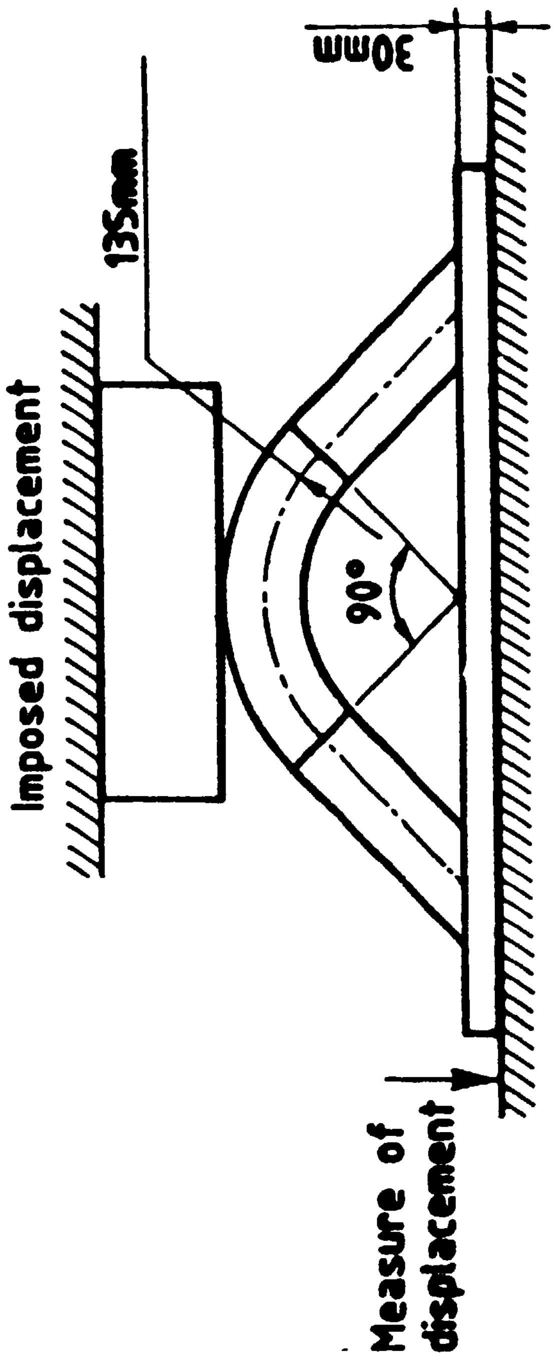


Fig. 9 - Static test for the determination of local crush rigidity of the elbow

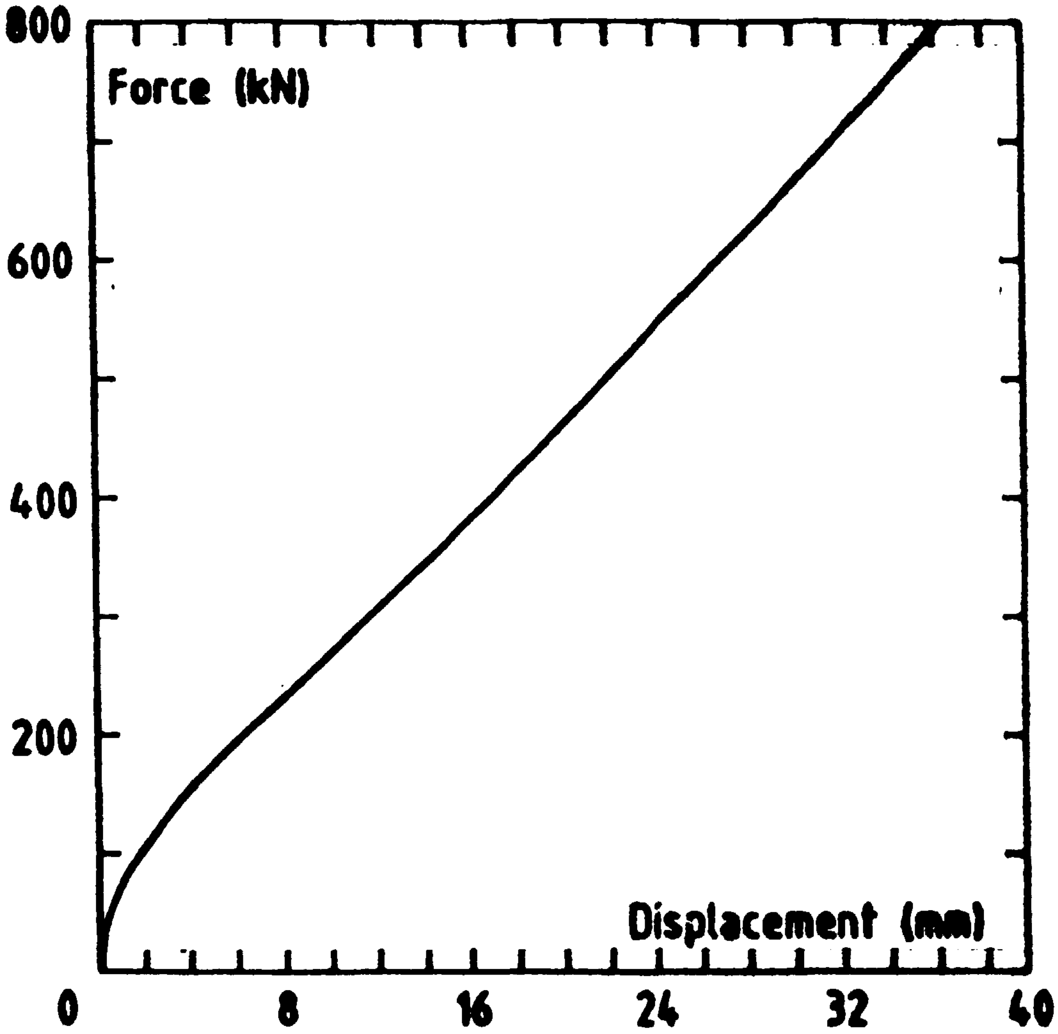


Fig. 10 - Load - Displacement curve

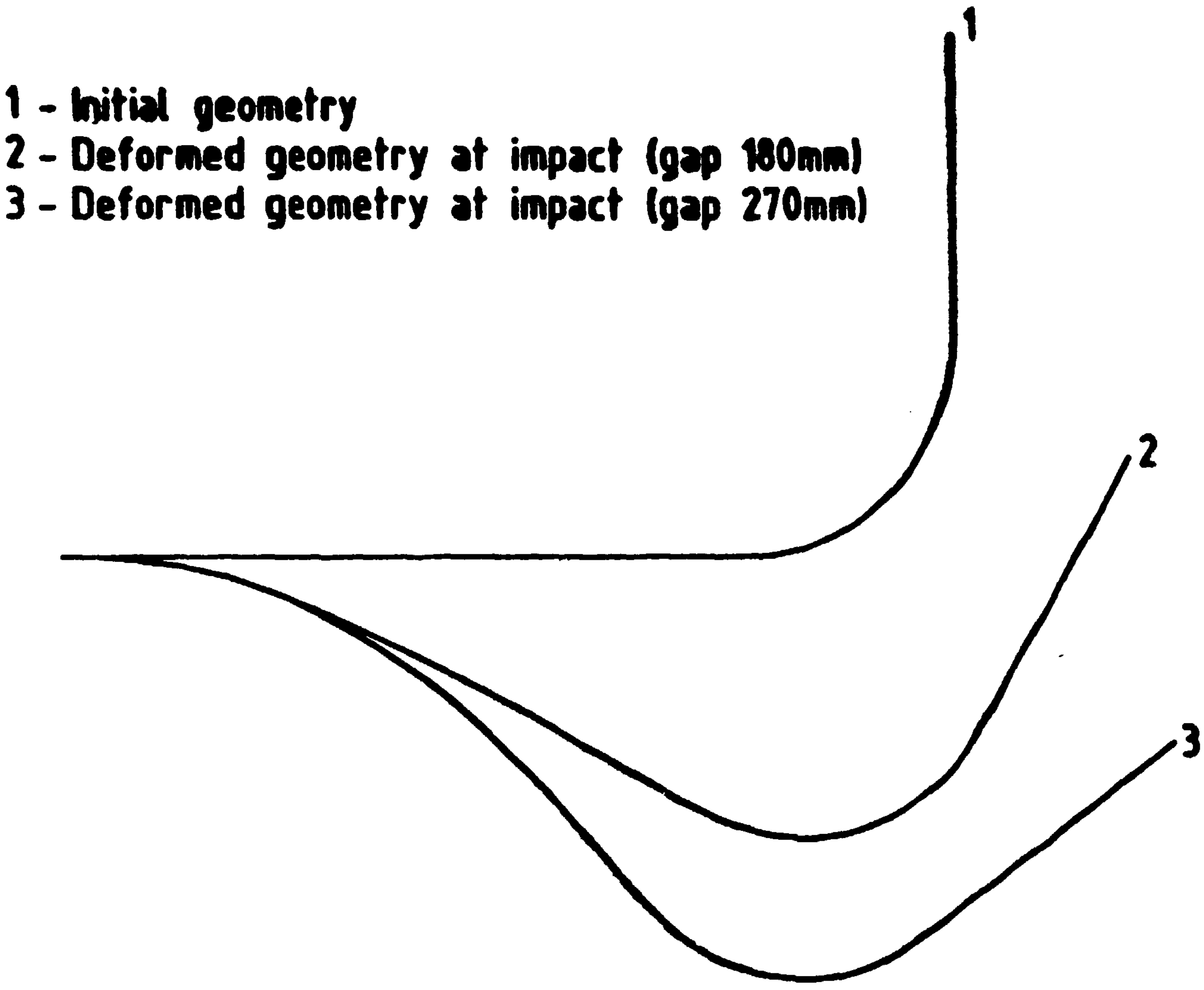


Fig. 11 - Caculated deformed geometry at impact

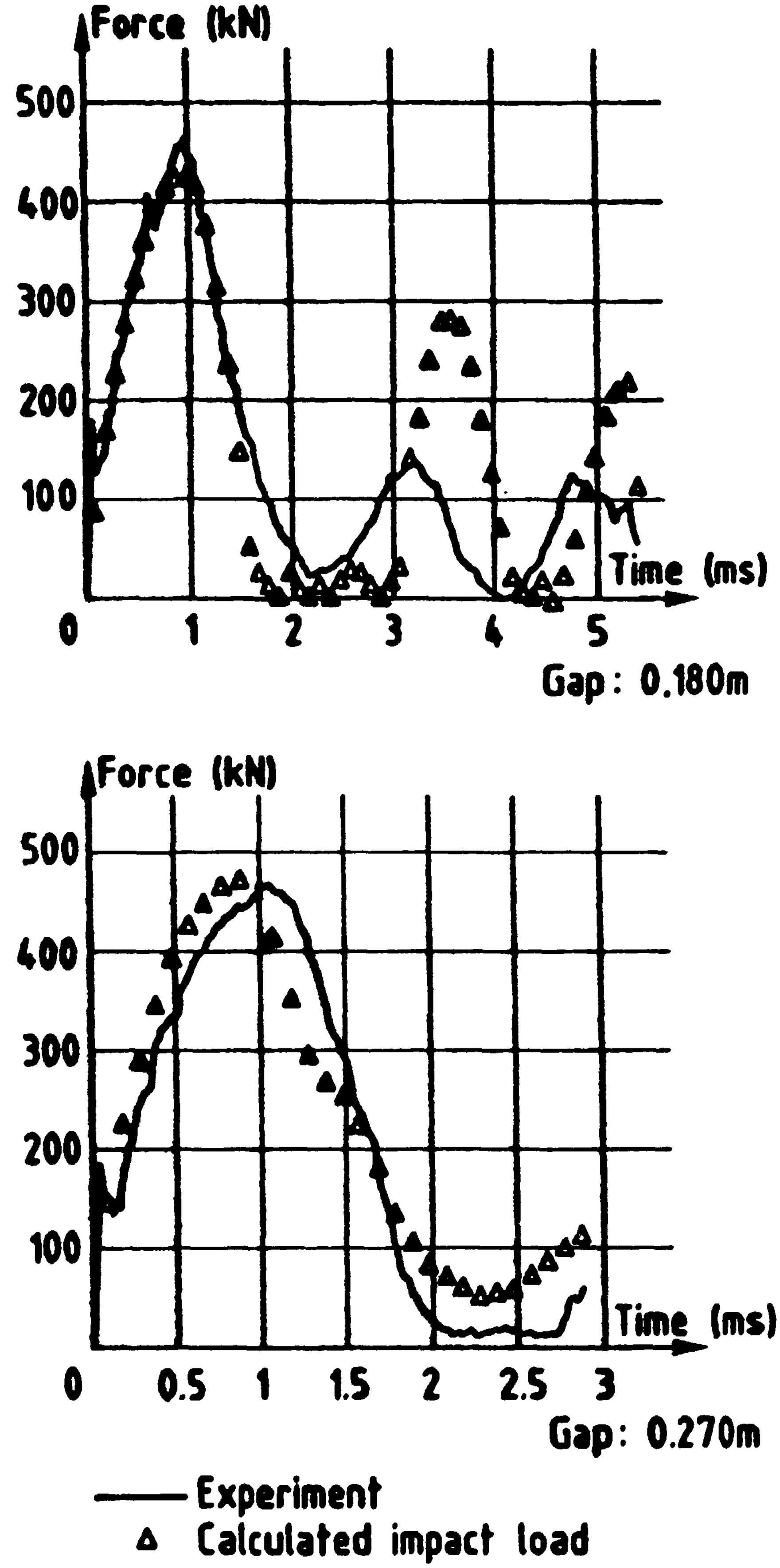


Fig. 12 - Calculated and experimental impact load