EXPERIMENTAL ANALYSIS OF AN ENERGY ABSORBER FOR STEAM PIPE RESTRAINT

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SUMMARY

This analysis is relative to a new high energy crushing dissipator device. This element is settled by a metal circular tube with circular holes, regularly distributed on its lateral surface. The working mode for this tube is axial crushing.

The first attractive characteristic of the system is its deflection versus applied force curve, which is close to the curve of a perfect shock absorbing device. That characteristic is obtained by the progressive flattening of the circular holes and a general "barrel" shape assumed by the tube during crushing. The second advantage is a great flexibility of adjustment between the level of energy to dissipate and the geometric parameters which define the stiffness (tube thickness, tube length, hole diameter, material...).

Characterization and qualification studies of the system were undertaken with full and half scale models. These models were crushed at low and several speeds, up to 23 meters per second at impact. The comparison between deflection curves recorded at low and rapid speed allowed for to point out the speed effects on the energy dissipation characteristics. It can be checked for example, that the dynamic deformation mode is substantially the same as that obtained by slow crushing with a press. Experimental results were completed by calculations employing the finite element method in elastic-plastic regime, using large elongation and deformation modes.

That energy dissipator element is original and is widely usable for various technical applications. The first industrial applications are in the nuclear field, in particular for lowering impact loads on concrete structures due to whipping steam pipe in case of rupture. Four energy dissipator units are mounted in a steam pipe restraint. They are located between the pipe and the concrete, and placed in parallel with a plate on top of them for load redistribution. The total restraint is completed by U-shape cables attached to a metallic base plate fixed on the concrete by means of pretension bolts. The design requirements of such a restraint were to limit the displacement of the pipe in any direction around its axis. Assumptions on the type and locations of the breaks are both guillotine and split breaks, anywhere along the pipe.

Previous design of steam pipe restraints were made of built-up arch shape metallic structures fixed on concrete, and equipped with three sets of stainless steel cables working on directions 120° apart. This design has the drawback of being bulky, heavy and costly.

The weight decrease of the metallic structures of the present design was made possible by using the crushing units which avoid the metallic arch. Energy absorbers working in compression instead of tension permit to eliminate the stringent 50% limit of the maximum uniform plastic elongation imposed in tension members.

Other applications for these absorber elements can be found in protection and limitation of mechanical consequences of accidents related to safety.

1. Introduction

To limit the mechanical consequences of postulated failures in nuclear reactors, protective measures must be taken [1] [2]. In particular pipe restraints are to be provided around high energy pipes in order to limit their motion in case of ruptures, and to avoid damaging equipment vital to the safety of reactors, or necessary to bring it to an orderly cold shutdown. These restraints are generally anchored on concrete or fixed on metallic structures which must be designed to withstand the dynamic loads resulting from the impact of the whipping pipe. For some large pipes, these loads may reach more than 500 KdaN (1000 Kips).

In order to decrease these loads, it is necessary to provide some energy absorbing elements which behave plastically when the load reaches some fixed value in order to absorb the kinetic energy of the impacting pipe or other type of missiles...

This paper describes such an energy absorber and its characteristics, and gives a direct application for a steam pipe restraint.

2. The Technical problem

The problem which had to be solved was to define an energy absorber capable of absorbing a great amount of energy in a reduced space ; therefore the "stroke" of the absorber was limited.

The design characteristics of the element were the following :

- Energy to be absorbed : 240 kJ
- Maximum stroke : 100 mm
- Maximum load : 250 KdaN
- Speed of impacting pipe : 10m/s.

It is well known that the perfect energy absorber is an element which has a curve of applied load versus deformation straight and parallel to the abscissa axis, because for a given stroke and a given energy to absorb, it yields the minimum load, which is generally looked after in order to reduce the strength capacity of the bearing structures.

Past experience with different energy absorbers led us to think that the needed characteristics would be obtained with a short metallic tube drilled with regularly distributed radial holes, working in axial compression.

3. Description of the energy absorber

The element is shown on figures 1 and 2.

The chosen tube is thick in order to ensure a good mechanical stability when local deformations occur during axial crushing.

Hole diameter is a parameter which can be adjusted to obtain the desired mechanical characteristics.

The developed lateral surface shows that the structure is composed of identical elementary cells (see fig. 1).

The strength of such cell can easily be determined using the finite element method as it will be shown later. But tests are the most straightforward way to obtain the mechanical characteristics.

Half scale specimens were used to optimize the characteristic of the absorbers. Their dimensions were :

. Outside diameter : 112 mm
. Height : 112 mm
. Six rows of 12 equidistant holes
. Material : Austenitic stainless steel : AISI 304-L grade.

The specimens were statically tested on a hydraulic press ;

The results are shown on figure 3. Different hole diameters were tested; the results show that the curves are nearly homothetic.

The maximum crushing stroke is 72mm i.e. 64% of the initial height. In fact in the calculations the energy taken into account is limited to a 50mm crushing stroke, which represents 45% of the initial height. This means that additional crushing capability is still available before the curve reaches the point were the load increases very rapidly with deformation.

The efficiency of this energy absorber defined as the amount of energy absorbed per unit of mass of the material is excellent.

Table 1 gives different values of this efficiency, which varies from 20 kJ/kg for stainless steel to 10 kJ/kg for aluminum.

4. Dynamic mechanical characteristics of stainless steel

It is now well established that the stress-strain curves which define the mechanical properties of metals vary with the speed of deformation.

In order to obtain these dynamic characteristics, tests were performed on samples taken from the same tube as the one of half scale models.

The testing machine is shown on figure 4.

The specimens used for these tests were standard tensile specimens. They were ruptured using a vertical dropweigth method. The energy of the drop weight at the time of impact was chosen to be slightly above the energy necessary to break the specimen.

In this test the speed is constantly decreasing up to nearly zero.

Thus it simulates the speed variation obtained during an impact of a missile on a soft target where the speed of deformation goes from an initial value to zero.

Fig. 5 shows the stress-strain curves obtained for different values of impact speeds. The results show a decrease of 15% of the maximum elongation obtained for static-tests.

The yield and initial plastic region is greatly raised for the speeds ranging from 0 to 10 m/s. However the tensile strength is not much affected by the speed. All these results are in good agreement with those published in the litterature [3] [4].

5. Dynamic characteristic of the energy absorber

Dynamic crushing tests were performed in order to determine the influence of the speed of deformations mainly initial impact speed, on the characteristic behaviour of the element during crushing. The half scale models were used and tested on a machine similar in principle (except for the dimensions) to the one used for testing the tensile specimens. The test installation is shown on figure 6. The range of impact speed vary from 9,8m/s to 23 m/s.

The results obtained are given in table II and fig 8.

They show that :

For an identical crushing stroke, the energy absorbed during a dynamic test can be from 10% to 20% higher than during a static test, for limited values of crushing. The increase is only 10% for complete crushing.

The absorbed energy increases with increasing initial speed :

- The increase is more sensitive on samples having a low characteristic curve.
- The maximum (peak) load is increased by the speed of deformation. However the comparison is not easy as the static and dynamic curves are quite different (see fig. 3 and fig. 7).

Some practical difficulties were encountered during the recording of the force measured with load cells because of the filter effect, which reduced the peak. For that reason, the values of maximum loads given in table II are to be taken with care. However the peak load increases sharply with increasing impact speed, the increase being of 30% to 50% at 20m/s.

A few dynamic crushing tests were made on full scale models. These tests were performed with the French National Railway facilities. The models were crushed between 2 carriages loaded with 80 tons of powder coal. The models were fastened on the fixed carriage. The kinetic energy was adjusted in fonction of speed of the rolling carriage. A film of this test was made.

6. Finite element analysis of a model

One of the tested model was analysed with the finite element method ; using the plastic large deformation option of the computer code named CEASEMT which is developped by the Commissariat à l'Energie Atomique.

The mesh used is shown in fig. 9. The result of the calculation is shown in fig. 10 and can be compared with the test results. There is a 10% difference between the two curves which is not bad considering the very complexe type of deformation of the structure

7. Application of the energy absorber to a steam pipe restraint of a pressurized water reactor

As mentioned earlier, the safety analysis of nuclear reactors requires that ruptures be considered in all high energy pipes such as the steam pipes of pressurized water reactors which have a large diameter and generally a long routing inside the reactor building. Ruptures of such pipes involve high hydrodynamic loads applied to the broken legs, which, if left unrestrained could damage safety related equipments or other smaller pipes.

Two types of breaks are postulated :

- . "guillotine" or circumferential, with complete severance of the pipe
- . longitudinal (or split)

The salient characteristics of a restraint are the following :

- . It has to work in all radial directions in order to be effective in case of longitudinal breaks.
- . It must not hinder the thermal movement of the pipe during normal heat up or cool down.
- . It must minimize the local heat loss : however a compromise must be found between the total gap and the heat loss.
- . It must minimize the loads on the bearing structures. To obtain this goal, materials undergoing controlled plastic deformation must be provided between the pipe and the bearing structure.
- . It must not prevent local in service inspection.
- . It has to be as economical as possible.

Many designs of large pipe restraints have been developped in the past years in the nuclear field. The types vary greatly because of specific requirements or lay-outs or load carrying capacity of available supporting structures, particularly when back fitting was involved. However the various restraints can be classified into two categories.

. Unidirectional restraint : i.e. restraint working in one radial direction only, or in one angle of the plane orthogonal to the pipe centerline.

. Omnidirectional restraint : i.e. restraint working in all directions of the plane orthogonal to the pipe centerline.

In the first category the design most commonly found is composed of U shaped bars or cables, generally made of stainless stell and mounted in parallel to a clevis arrangement fixed on a base plate anchored to the supporting structures.

In the second category, the system is obviously more complex and bulky, as it must protect the bearing structure itself from direct impact of the broken pipe. A typical restraint is shown on fig. 10. It is composed of

- an arch made of welded steel structure which is fitted around the pipe and fixed on the bearing structure. Its role is to support the cables or bars and transfer the load to the bearing structure.

- A sleeve coaxial to the pipe

- The energy absorber which can be made of stainless steel cables or bars attached to the welded structure and fixed around the sleeve.

The restraint presented here under is derived from the one just described. The concept of restraining the pipe in all radial directions is kept. This could have been achieved by replacing the cables by a number of E.A. elements described in the first part of this paper. However due to local lay-out requirements, a restraint less bulky had to be developed. The welded frame was eliminated and some of the cables were replaced by the E.A. working in compression. The principle of the restraint is given in fig. 12.

It consists of :

- A welded structure composed of a base plate and two "boxes" to which cables are attached. The baseplate is anchored to the concrete wall by means of pretensioned tie-rods.
- A sleeve coaxial with the pipe which maintains the cables
- Four stainless steel cables having the following characteristics
  - . Diameter : 80mm
  - . Maximum elongation : 45%
  - . Load capacity : 185 KdaN
  - . Length ≃ 4.2 meters.
- The concrete structure is protected from direct impact by four energy absorbers mounted in parallel between the two cable anchor boxes.

In fact with the specific parameters : gaps, hydraulic driving force, only 2.3 E.A. were found necessary to absorb the kinetic energy of the impacting pipe. However to protect the wall completely from a break propulsing the pipe towards the wall, four E.A. were necessary.

The classical energy balance method used to obtain the maximum compressive load applied on the concrete structure in case of a longitudinal break at the level of the restraint gave about 560 KdaN with the following parameters :

. Constant hydraulic driving force : of 320 KdaN

. Initial gap of 50mm.

This system yields an overall dynamic load coefficient of less than two.

8. Conclusion

An energy absorber working in compression has been developped, and its application to a large pipe restraint presented. Other applications of such an element can be found when very large amount of kinetic energy has to be absorbed in compression. It is interesting to notice that systems absorbing energy in compression are not limited by the 50% maximum uniform elongation rule which may seem in some cases over conservative.

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Rapport HEDL - TME 71 - 164 Novembre 1971

TABLE I

ENERGY DENSITY OF VARIOUS MODELS OF ENERGY ABSORBER COMPLETELY CRUSHED.

Material	hole diameters mm	Absorbed energy KJ	Mass kg	Energy density KJ/Kg
Stainless Steel AISI 304L	16	39,7	1,85	21,5
	17	34,9	1,69	20,6
	18	29,1	1,52	19,1
	19	25	1,33	18,8
Mild Carbon Steel	17	27,4	1,69	16,2
Aluminum	17	5,6	0,58	9,6

TABLE II

TEST RESULTS

Test Number	Hole diam. mm	Impact speed m/s	Reference crushing mm	Absorbed energy (Dynamic) ED: Joules	Absorbed Energy static ES : Joules	Ratio $\frac{ED}{ES}$ %	Peak Force (Dynamic) FD 10^4N	Peak Force (static) FS 10^4N	Ratio $\frac{FD}{FS}$ %
2	19	10	50	16880	13930	121	40,5	38,5	105
			75	24940	22460	111			
4	19	14,6	50	17280	13930	124	46,5	38,5	121
			75	24430	22460	109			
5	17	9,8	50	24930	22560	110	59,5	56,6	105
6	17	14,6	50	25900	22560	115	63,6	56,6	112
9	17	19,8	40	20800	17220	121	68	52	131
12	17	19,8	40	20000	17220	116	78	52	150
11	17	21,4	40	18800	17220	109	75	52	144
10	17	22,8	40	20100	17220	117	70	52	135

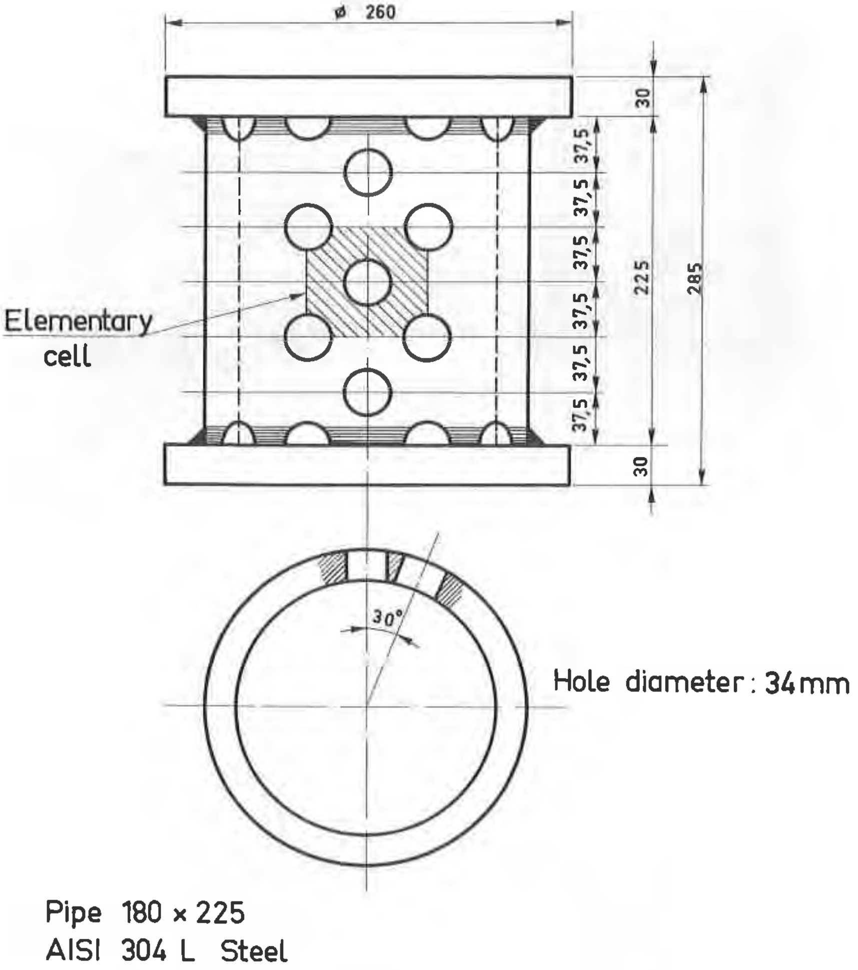


Fig. 1 : Sketch of the energy absorber

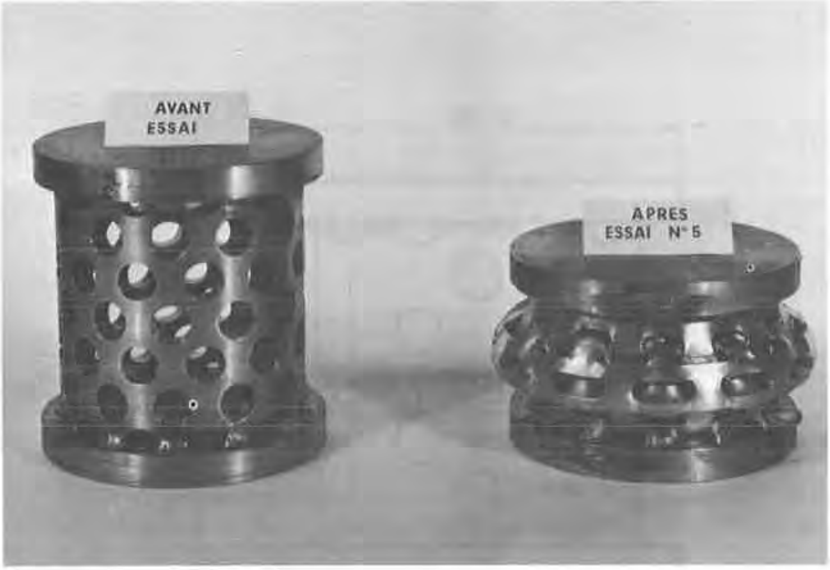


Fig. 2 : Photograph of an energy absorber before and after crushing.

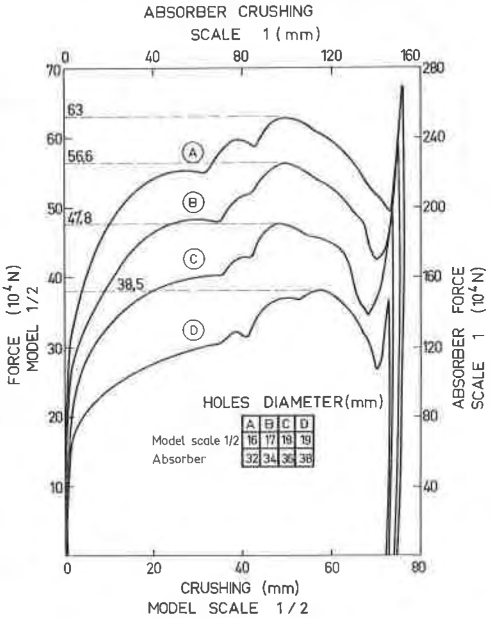
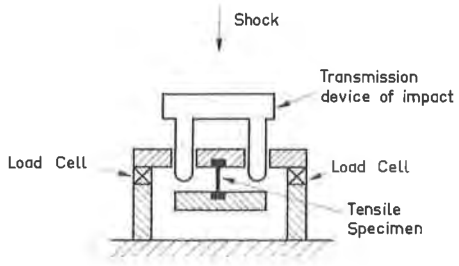


Fig. 3 : Curves of loads versus static deformation of the Models.



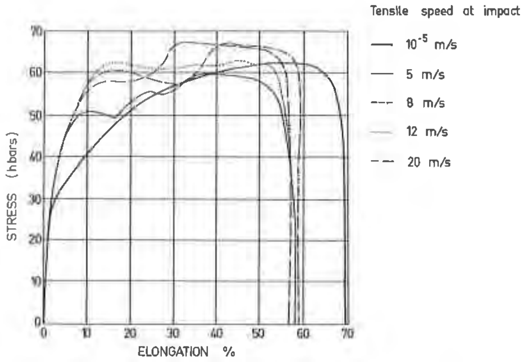


Fig. 4 : Sketch of the testing machine for dynamic mechanical characteristics

Fig. 5 : Effect of the speed of elongation on stress strain curves of AISI 304 L steel.

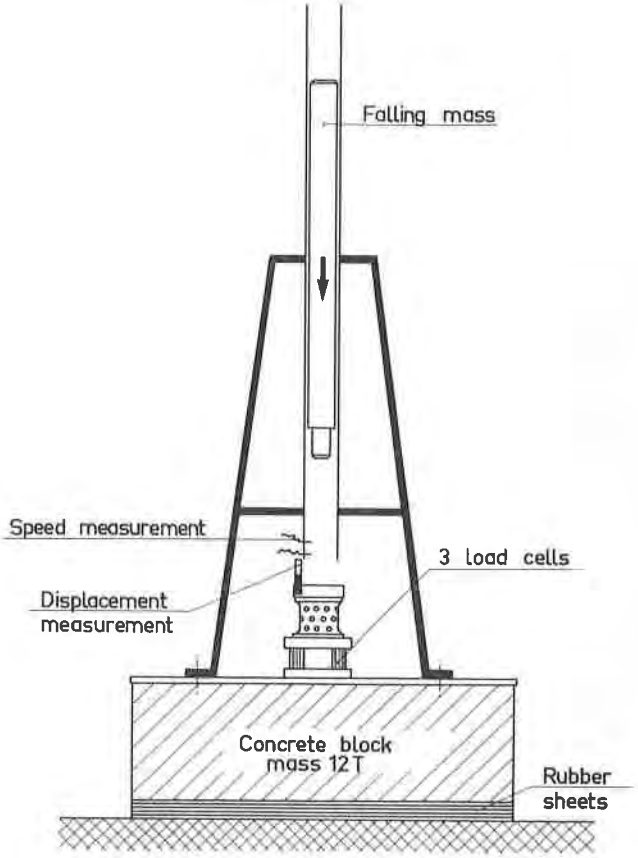
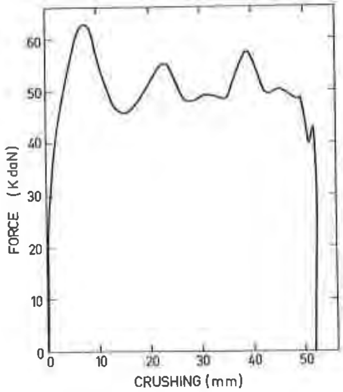


Fig. 6 : Sketch of the testing facility for drop weight on halfscale models.



TEST n° 7

Speed 15 m/s
Hole Ø 17 mm
Energy for 50 mm of crushing : 25.6 KJ

Fig. 7 : Typical dynamic crushing curve.

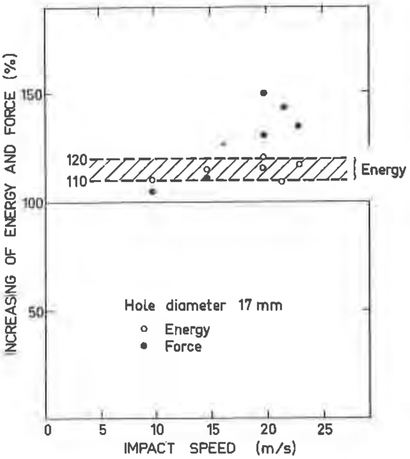


Fig. 8 : Influence of speed of deformation on dynamic characteristics.

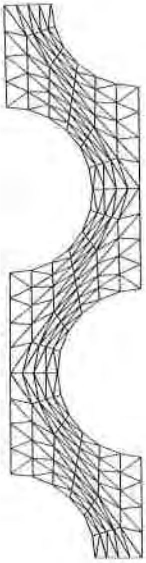


Fig. 9 : Finite element mesh of a model.

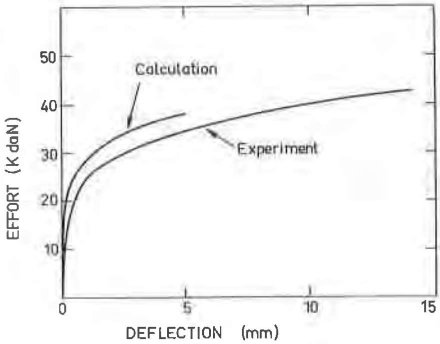


Fig. 10 : Comparison between finite element calculation results and tests.

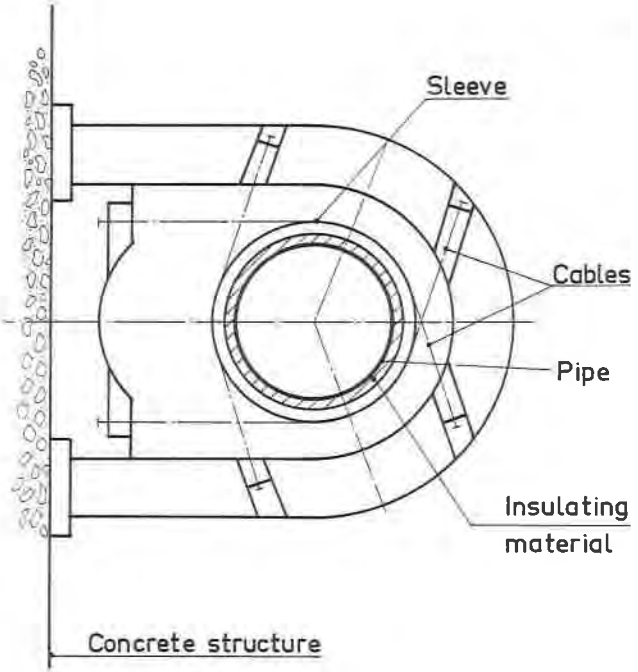


Fig. 11 : Typical omnidirectional pipe restraint.

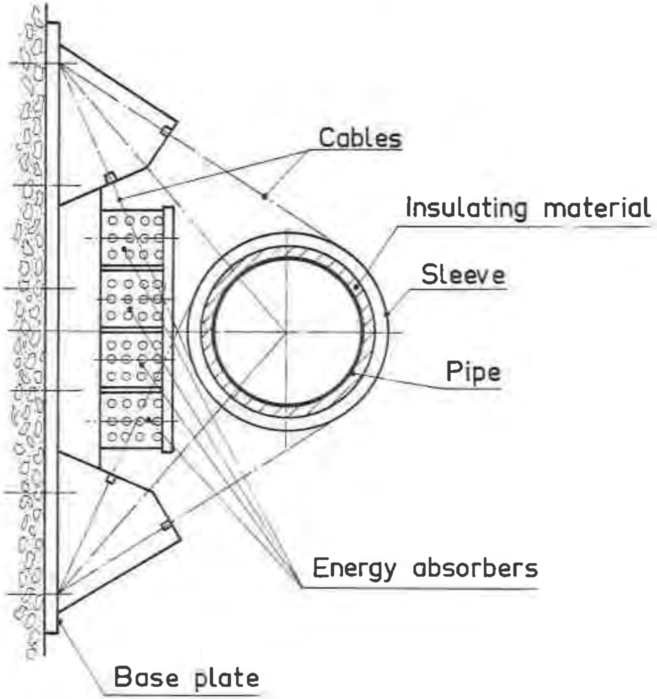


Fig. 12 : Pipe restraint using cables and compressive E.A.