

SAFETY OF PIPE WHIP RESTRAINTS

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Summary

Pipe whip restraints are used in nuclear power plants in order to limit the consequences of ruptured pipe whip effects and are thus an important part of the plant safety concept. The design of these devices is based on the choice of adequate construction and computational analysis supported by experimental investigation.

Pipe whip restraints should, by means of deforming components, be able to absorb the energy of a ruptured pipe accelerated by the fluid reaction force. Since the elastic deformation of the restraint material is not sufficient for this purpose, or would result in excessive anchor loads, pipe whip restraints must generally be designed to work in the plastic range. Two types of restraints are presented in this paper, including the description of their mode of operation, design and computation.

A comparison and critical evaluation of the calculation methods presently available are also given. The range of methods covers those developed for very simple models, as well as advanced expensive computational techniques such as dynamic finite element analysis with the help of which the design of pipe whip restraints in the plastic range can be performed. The comparison of, and the experience so far gained with, the computations show that, in most cases, pipe whip restraints can be safely designed by means of reasonably simple analytical models. The major parameters of such models are presented.

Ductility characteristics of the used stainless steel at various strain rates have also been determined, including the stress-strain curve and the ultimate uniform strain.

Construction, design, computations and tests show that the chosen types of pipe whip restraints meet the requirements adequately.

1. Introduction

The choice of a specific type of pipe whip restraint depends mainly on the intensity and direction of the fluid reaction force which occurs subsequent to a pipe rupture, on the particular conditions in the vicinity of the break, such as piping geometry, and location of elbows, on the nature of endangered components and structures, and on cost.

The first step is to define the location of breaks which are assumed to occur, and to determine the fluid reaction forces at the rupture point. This makes it possible to establish a concept for pipe whip restraints, and to define the tasks and the locations of the pipe whip restraint structures. These are then designed, and a dynamic stress analysis is performed.

In what follows, the necessary investigations and the construction of two typical groups of pipe whip restraints are in the above stated order presented.

Additionally, the results of static and dynamic tests performed for plasticizing materials and pipe whip restraint components are described.

2. Definition of the Concept for Pipe Whip Restraints

In order to give an example of this safety concept, the pipe whip restraints for the feed water lines within the containment of KWU's Standard 1300 MW Plant will be described. The geometry of the pipes and the location of pipe whip restraints are shown in Figure 1.

The following components and system parts are protected by this restraints:

<u>Component or system part</u>	<u>Restraint No.</u>
Steel containmentshell	2; 3
Accumulators	4; 5
Containment penetration	1
Fixed point	1
Building for recirculated air system	6; 7; 8

In the vicinity of the penetrations, such restraints must be used to reduce the loads to acceptable values by using relatively small deformation amplitudes, whereas, in the vicinity of the missile shielding cylinder, it is possible to use restraints with larger deformation capability.

3. Design of Pipe Whip Restraints

Figure 2 shows a typical design for a restraint with a small gap. It has the same deformation properties in all directions. The energy of the ruptured pipe is absorbed by the plastic deformation of crushable pipes made from stainless or tough ferritic steels. These pipe whip restraints can be used where only small displacements of the pipe in any direction are permissible, where double pipes must be restrained, where bellows must be protected, or where this mode of construction suggests itself for structural reasons (as, for example, in the case of penetrations).

For this design, the smaller gap has also the advantage that the dynamic forces in the pipe whip restraint are smaller than in pipe whip restraints with larger effective clearances.

Figure 3 shows a typical U-bar design with a larger clearance. The energy of the accelerated pipe is absorbed in the U-bar. The U-bar is constructed of austenitic steel which has a high energy absorption capacity under significant uniform elongation.

In addition to the careful design of the U-bars, its anchoring must also be adequate designed. The design shown in Figure 3 includes a light steel structure which is able to transmit considerable tensile and transverse forces into the concrete wall.

4. Plasticizing Elements, Computation and Experiments

The careful design of the plasticizing elements is decisive for the proper function of the pipe whip restraints. In addition to computations carried out in support of a particular design, tests were performed for confirmation.

4.1 Crushable Pipes

The plastic behaviour of the crushable pipes used in the restraints of the type shown in Figure 2 is represented in Figure 4. The experimental results, force-deformation diagram, and the curve $F_{spI} = f(\delta/D)$ for pipes made of St 35 and having an outer diameter of 159 mm and a wall thickness of 16 mm are shown in this Figure.

With the help of the typical curve $F_{spI} = F(\delta/D)$, the force-deformation diagram of other (smaller) crushable pipes can be determined. The calculation formula at the same relative deformation δ/D is given by

$$F_{sp} = 0,6644 \frac{t^2}{D} F_{spI} \quad \text{eq. (1)}$$

For steels for which the material law $\bar{\sigma} = K \bar{\epsilon}^n$ applies, a calculation formula of the specific deformation force is given by

$$F_{sp} = m \frac{2Kt^{n+2}}{n+2} \cdot \frac{(D+t)^{n-1}(D-\delta)^n + \delta^n D^{n-1}}{D^n (D+t)^{n-1} (D-\delta)^{n+1}} \quad \text{eq. (2)}$$

where:

- D — average diameter,
- δ — pipe deformation,
- t — wall thickness,
- K, n — steel material properties,
- m — coefficient.

The following values apply for the tested model made of austenitic steel 1.4541:
 $K = 652.4 \text{ N/mm}^2$; $n = 0.0823$; $m = 0.5$. The curve shown in Figure 5 results from this formula. It agrees well with the experimental data.

4.2 Austenitic U-bars

The plastic properties of plasticizing U-bars were confirmed by several dynamic experiments.

The influence of strain rate on the tensile strength, yield point, elongation to fracture, percent uniform elongation, and area reduction of the X 5CrNi 18.9 material is shown in Figures 6 and 7. When the strain rates are high, percent elongations of about 40 % before reduction result for short specimens. Longer specimens lead to values of 50 - 55 %.

The design of the transition between the plasticizing U-bars and the elastically designed anchoring was determined by means of experiments which tested its load-carrying capacity. In Figure 8, the corresponding results are shown as a function of the tap depth in the threaded connection. The selected design is shown by point A. The safety margin between the actual load and the curve representing the load-carrying capacity can be clearly seen from this figure.

5. Pipe and Restraint Computations

For the computation of an elastoplastic system consisting of a pipe and its pipe whip restraints, special computational methods are required, which go beyond the usual dynamic structural analysis in the elastic range. The plastic behavior of the system can be analyzed by means of simple theoretical models, as well as by finite element methods which require higher costs.

It is important to select an appropriate computation method, since too expensive models result in high handling and computation costs, whereas too simple computation models result in a considerable accuracy reduction.

In order to select an appropriate method of dynamic analysis, a piping system has been calculated by means of three different methods. These methods are:

- a) Numerical integration of the equation of motion of a simple elastoplastic model with one degree of freedom.
- b) Improved modelling of the system with two plastic hinges at the pipe, i. e. a system with two degrees of freedom, by means of the PDAN program.
- c) Computation by means of the PIPERUP elastoplastic piping program, which uses the finite element method.

All three methods take into account the gaps and the elastoplastic properties of the pipe whip restraints. The models and results are shown in Figure 9.

The agreement concerning the force and the deformation in the pipe whip restraints can be described as good. Complete data concerning the strain level in the pipe can be obtained with the last-mentioned computational method; however, this value is of secondary importance when the pipe is ruptured. The comparison shows that useful results can be obtained if the governing parameters are selected carefully and simple computation models are used.

In particular, simple models are indispensable for the preliminary design of pipe whip restraints.

6. Final Remark

Pipe whip restraints are used to prevent further damage that may be caused by ruptured pipes in nuclear power plants. A suitable construction, the use of tough austenitic and ferritic steels, a complete dynamic analysis of the system consisting of pipe and pipe whip restraints, careful design of the components, supporting tests, and high quality manufacturing, and erection and inspection procedures result in a safe structure for such protective devices.

References

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- / 3 / KWU und MPA-Stuttgart, "Zugversuche an dem austenitischen Stahl X 5 CrNi 18.9, Werkstoff Nr. 1.4301 mit Dehnungsgeschwindigkeiten im Bereich von 10^{-4} /s bis 100/s bei Raumtemperatur und bei 150 °C, 1978.

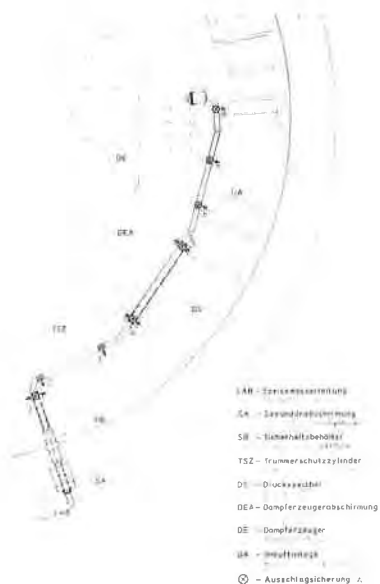


Fig. 1 Feedwater line; location of the pipe whip restraints.

- LAE - Zerlegbarerleitung
- SA - Sarandrohrschirmung
- SB - Sicherhaltbehälter
- TSZ - Trimmergeschützylinder
- DE - Druckspindel
- DEA - Dampferzeugerabschirmung
- DE - Dampferzeuger
- DA - Dampfmessung
- ⊙ - Ausschlagsicherung

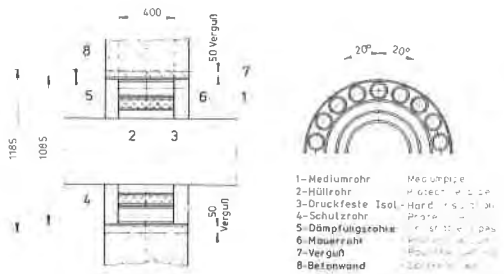


Fig. 2 Restraint with crushable pipes.

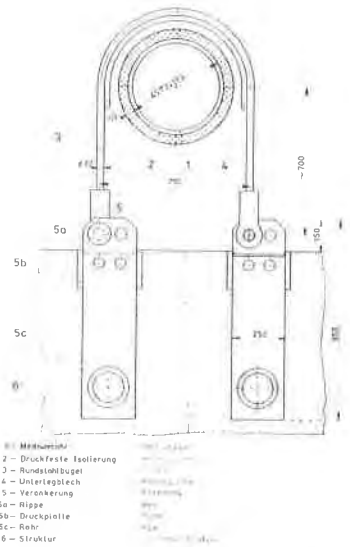


Fig. 3 U-bars restraint.

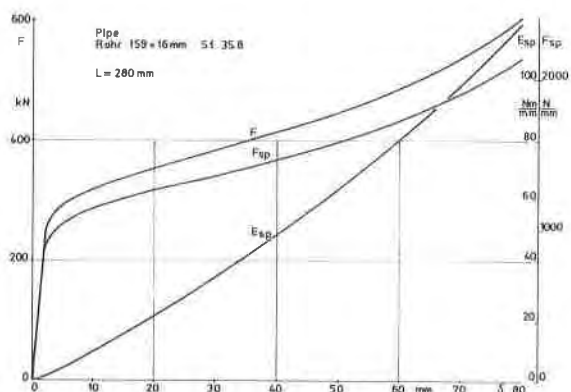
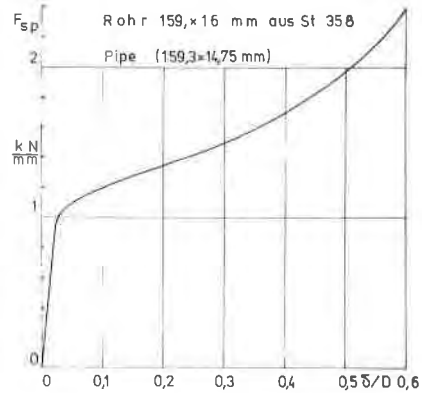


Fig. 4 $F_{sp} = f(\delta/D)$; $F = f(\delta)$; $F_{sp} = f(\delta)$; $E_{sp} = f(\delta)$

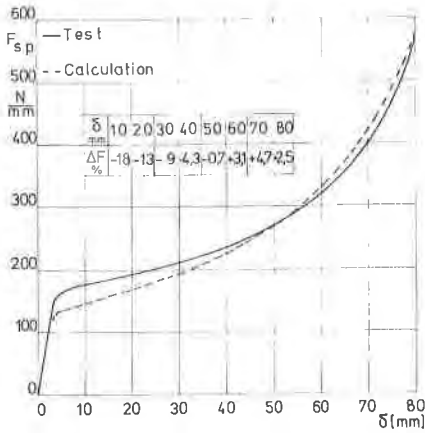


Fig. 5 $F_{sp} = f(\delta)$; Pipe from the stainless steel 1.4541.

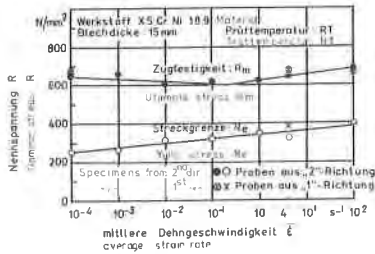


Fig. 7 Influence of strain rate on yield and ultimate stresses at room temperature.

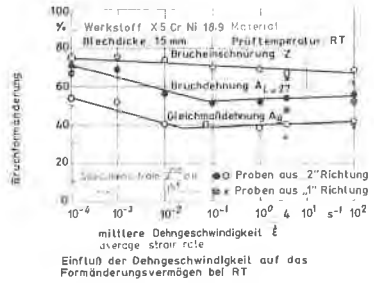


Fig. 6 Influence of strain rate on the ultimate and uniform strains.

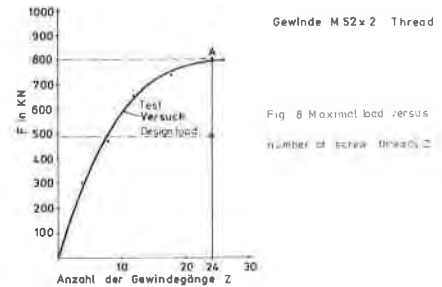
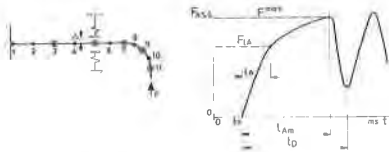
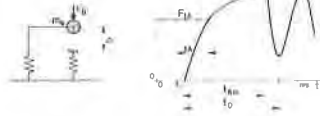


Fig. 8 Maximal load versus number of screw threads.

PIPERUP-Program



Feder-Masse-System
Spring-mass system



PDAN Program

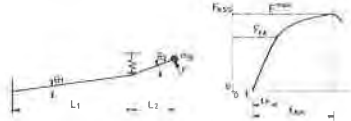


Tabelle: Vergleich der Ergebnisse Results

Größe Methode	Fmax [N]	tASS [ms]	tAm [ms]	Ya [mm]	Yc [mm]	t0 [ms]	V10 [m/s]
System mit 1 Frühabgleich	2,5	48	3,07	5,8	100	7,8	1,94
PDAN	2,3	44	272	54	93	8,5	2,10
PIPERUP	1,8/1,8	20/28	2/2/0	30/38	107/204	8,5	

Fig. 9 Computational models.