PIPE WHIP RESTRAINTS - PROTECTION FOR SAFETY RELATED EQUIPMENT OF WWER NUCLEAR POWER PLANTS

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Abstract

The paper concerns the problem of enhancing the protection of WWER NPP equipment against the effect of a high energy piping break which results in a pipe whip. A pipe whip restraint has been designed in order to protect nearby safety related systems and components. The pipe whip restraint properties have been optimized using results of iterative non-linear dynamic analyses of the piping system response to forces due to fluid streaming out of the broken pipe.

1. Introduction

The nuclear power plants of the WWER type operate for about three decades in several countries. In the Czech Republic, the Dukovany NPP of the VVER-400213 type has been put into operation in 1985. A steady very high level of plant's operational safety, availability and reliability has been unambiguously proved. An effective way of managing updated safety requirements ensures a high safety level for the whole plant's design life. In accordance with general trends, operation of the plant in excess of its design life is assumed. An effective ageing management of systems, structures and components is decisive for maintaining operational safety during the extended plant's operating lifetime. Moreover, due to steadily increasing additional requirements, the plant's operational safety has to be enhanced. Besides many other important problems, those related to the safety of operating NPP piping network have to be considered.

Large diameter piping conveying high pressure, high temperature feedwater or steam through densely equipped nuclear power plant areas is considered as a very important safety-related equipment. These pipes are highly stressed and despite all sophisticated precautions a failure cannot be definitely excluded. Under certain extraordinary circumstances a sudden total break of the pipe in an exposed cross section should be considered. Since the high energy piping supporting system stiffness has to be relatively low, the piping dynamic response displacement to a break could be very large, endangering the adjacent structures, piping, cables and devices.

Various measures to control the whip of a pipe could be taken. Because of wide changes of both temperature and pressure involving large pipe displacements, such a piping system cannot be simply provided with closely spaced stiff supports, and hence special pipe whip restraints are designed. The intended function of the pipe whip restraint designed for the postulated break location must be reliably proved.

2. Formulation of the problem

The selected problem is formulated as follows: A sudden total circumferential break of a highly stressed pipe in the postulated cross-section results in the pipe whip. The protection of nearby safety related systems and components should be enhanced by an additionally mounted pipe whip restraint, bridging axially the postulated pipe break cross-section. The pipe whip restraint structure is provided with energy absorbing visco-plastic structural elements. This type of pipe whip restraint, based on [2], has been developed by SKODA PRAHA, a.s. industrial enterprise. The number, arrangement, dimensions and properties of applied visco-plastic elements should be optimized with respect to conditions specified for the considered NPP. The adopted criteria involve the limits of displacements and stresses of considered pipes. The optimalization procedure has been based on iterative non-linear dynamic analyses of the piping system response to forces due to the fluid streaming out of the broken pipe.

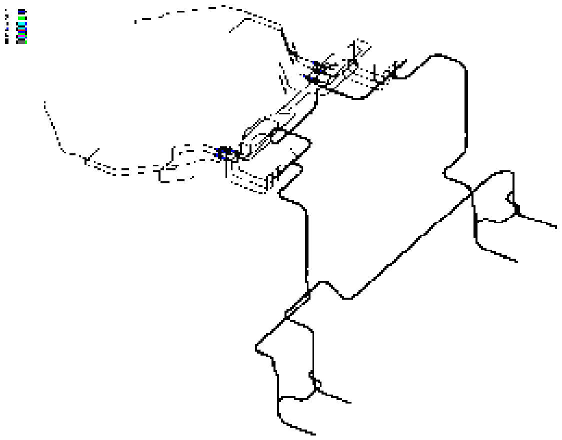

FIG. 1. NPP Dukovany – compution model of feedwater piping.

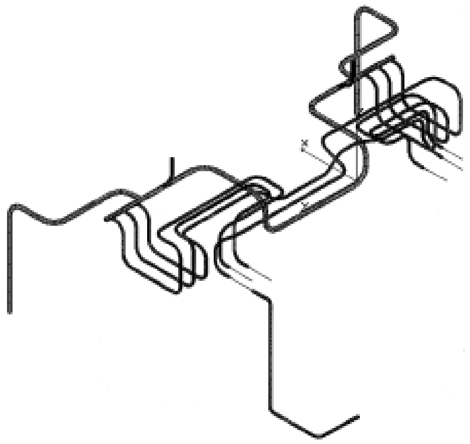

FIG. 2. NPP Dukovany – compution model of feedwater piping.

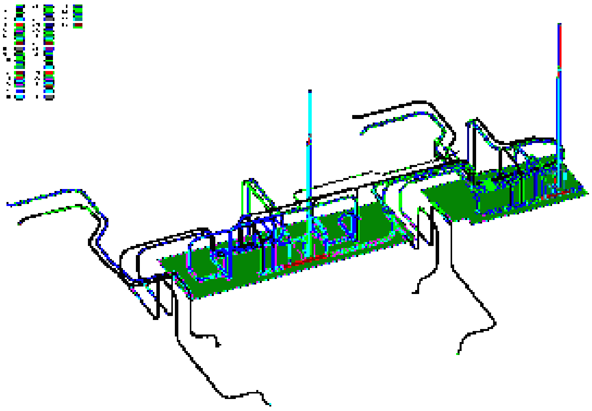

FIG. 3. NPP Dukovany – complete compution model of steam piping.

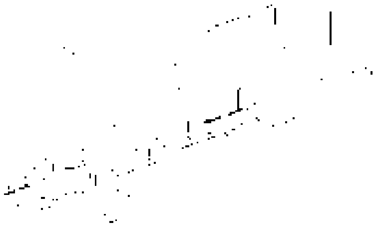

FIG. 4. NPP Dukovany – compution model of steam piping.

Such an approach has been applied in the design of pipe whip restraints for the NPP Temelin (WWER-1000 Model 320) and NPP Dukovany (WWER-440213), among others. The analyses have respected relevant clauses of [1] and [3]. The majority of the series of dynamic response analyses has been devoted to pipe whip restraints for NPP DUKOVANY. Particularly, the pipe whip restraints located at the primary containment penetrations have been analyzed. For one production block involving six steam generators, six pipe whip restraints of feedwater piping and four pipe whip restraints of steam piping have been analyzed in detail. The eighteen pipe whip restraints of remaining production blocks have been analyzed in a simplified way. Versions of pipe whip restraints for tee-pipes have been analyzed for ten postulated breaks. For NPP Temelín eight pipe whip restraints have been analyzed in detail. Basic concepts of performed analyses are described below.

3. Computation model

The computation model of the NPP Dukovany steam piping is used to illustrate the general approach in developing models for dynamic response analyses of piping systems with pipe whip constraints. For analyses of the NPP Dukovany steam piping system a spatial computation model with 343000 degrees of freedom has been developed using the FEM-based COSMOS program package. The model includes the complex of all interacting steam pipe runs and load bearing floor structures of the selected main production block of the plant. In order to ensure proper boundary conditions of the model, adjoining structures with weak interaction have been modeled in a simplified way. Large diameter pipes have been modeled using shell finite elements with material density values selected so as to attain overall mass distribution corresponding to pipe operating conditions. Branch pipes, piping supports, valves, etc. have been modeled using pipe, spring, beam and mass finite elements. Steel structures as well as reinforced concrete structures supporting the piping system have been modeled using combination of shell, beam and solid finite elements. General view of the complete computation model is shown in Fig. 3. The view of the computation model with the floor structures removed is shown in Fig.4. Partial view is shown in Fig.5.

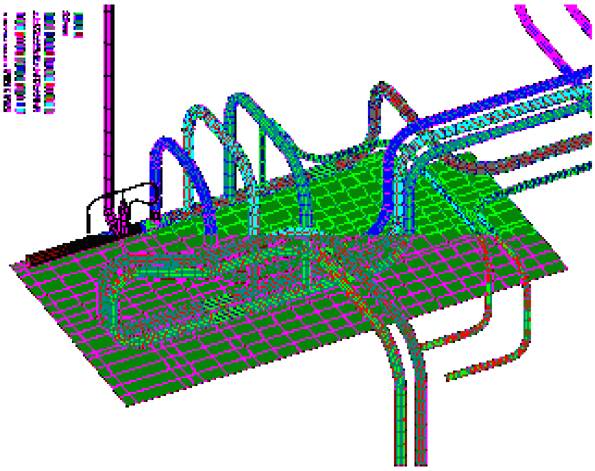

FIG. 5. NPP Dukovany – compution model of steam piping - detail

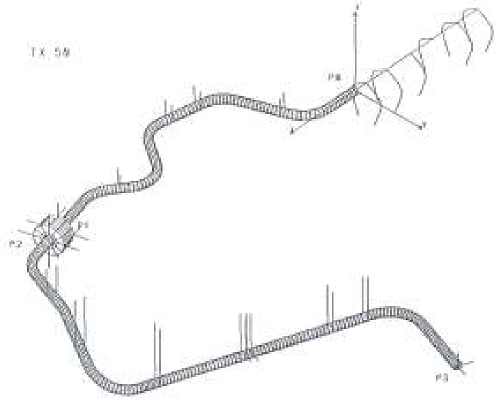

FIG. 6. NPP Temelin – compution model of steam piping

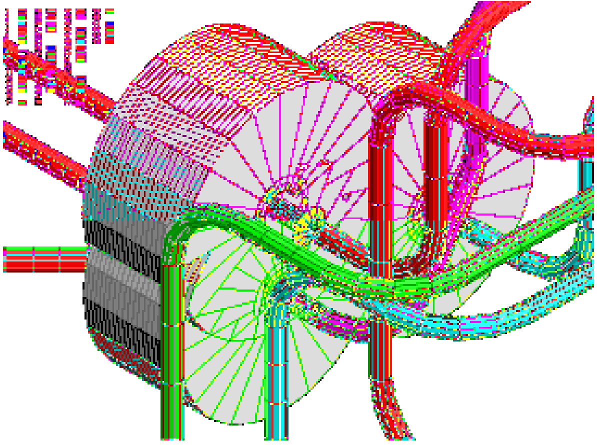

FIG. 7. Compution model of steam piping – containment wall zone

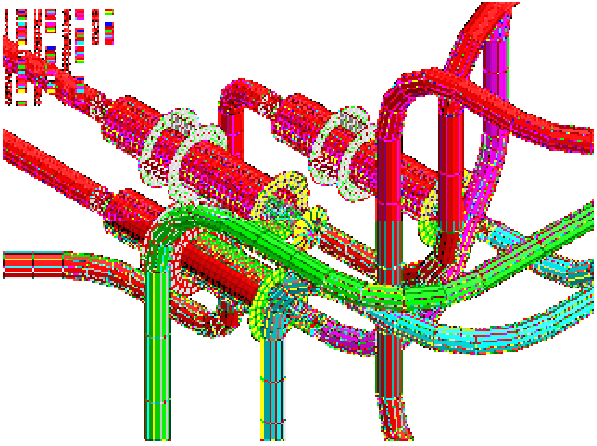

FIG. 8. Compution model of steam piping – containment wall penetrations

The mechanical structure of the pipe whip restraint has been modeled using a combination of shell, beam, truss and spring elements (see Fig. 9). Large displacements and non-linear properties of truss and spring elements modeling the visco-plastic energy dissipating structural members have been considered. The stiffness and damping properties of used gap finite elements have been defined as dependent on the relative displacement and velocity of their end nodes, respectively. The respective characteristic functions used in the analysis have been determined or proved experimentally (an example is shown in Fig.10 - generally see [2]). Alternatively, the function of the pipe whip restraint has been modeled by a set of variable forces. The steam piping system has been provided with six pipe whip restraints located on pipes just outside the containment wall hermetic penetrations (see Fig.7 and Fig.8). The effects of five pipe whip restraints located on tee-pipes (three of them are shown in Fig. 16) have been analyzed, too.

For illustration, computation model of the feedwater piping system of NPP Dukovany is shown in Fig.1 as well as in Fig.2. The sectional model of the steam piping of the NPP Temelin is shown in Fig. 6. The model includes the piping run section inside the containment, and the piping run section in the intermediate compartment with the pipe whip restraint located at the containment wall hermetic penetration.

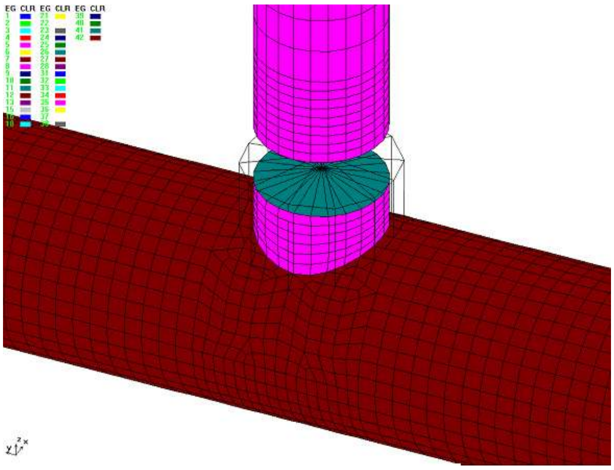

FIG. 9. *Compution model of pipe whip restraint*

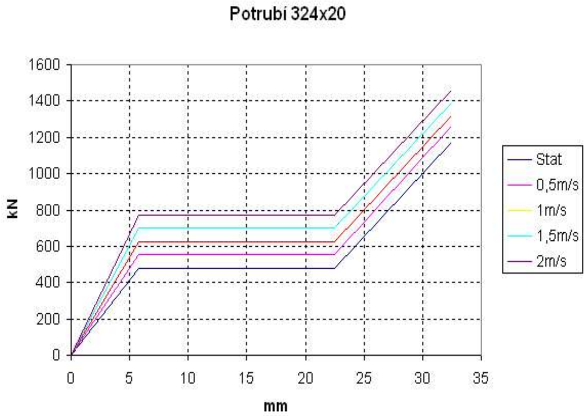

FIG. 10. *Characteristic function of pipe whip restraint*

4. Piping response analysis

The analysis of the postulated ruptured piping and pipe whip restraint system response to fluid dynamic forces is carried out using direct integration of the system equations of motion. The initial response analysis of the piping model without pipe whip restraint is used to estimate the extent of potential damages due to the pipe whip. The next analysis with preliminary designed pipe whip restraint characteristics shows the attained limitation of the pipe whip and yields the data required for the appropriate modification of characteristic functions of the pipe whip restraint. A series of repeated analyses leads to optimization of characteristic functions of the pipe whip restraint. Consequently a set of visco-plastic energy dissipating structural members is selected so as to fit the computed characteristics of the pipe whip restraint.

Each step of the analysis starts by increasing gravity, pressure and temperature loads from zero up to steady state values. During the break opening time, using a set of governing time curves, stress resultants in the postulated pipe section are decreased to zero. The effect of the steam streaming out of the broken pipe is introduced by both varying the pressure in the pipe and adding a system of variable external forces at the separated pipe ends. These forces depend on the instantaneous gap width between the broken pipe end sections and on the time as well. The forces developed by the pipe whip restraint in function depend on both relative displacement and relative velocity of the pipe whip restraint structure ends. The pipe whip restraint is modeled using a set of finite elements, the properties of which fit the pipe whip restraint characteristics applied in the instantaneous step of the computation procedure. Numerical integration provides time histories of all response quantities required for the assessment of the pipe whip restraint function.

The field of instantaneous response displacements of the broken branch pipe provided with the pipe whip restraint is shown in Fig.12. Time history of the axial component of the pipe whip restraint force is shown in Fig. 11. Time history of axial displacement of the separated pipe end is shown in Fig.13. Time history of axial displacement of the pipe end fixed to the body of the pipe whip restraint structure is shown in Fig.14. Fields of instantaneous stress intensities are shown in Fig. 15 and in Fig.16 as well.

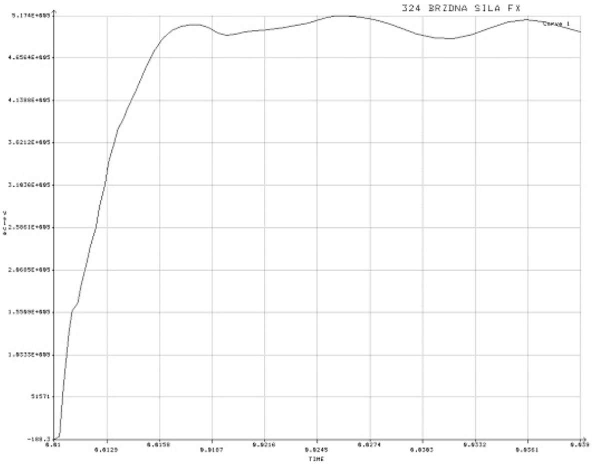

FIG. 11. Time history of axial force of the pipe whip restraint

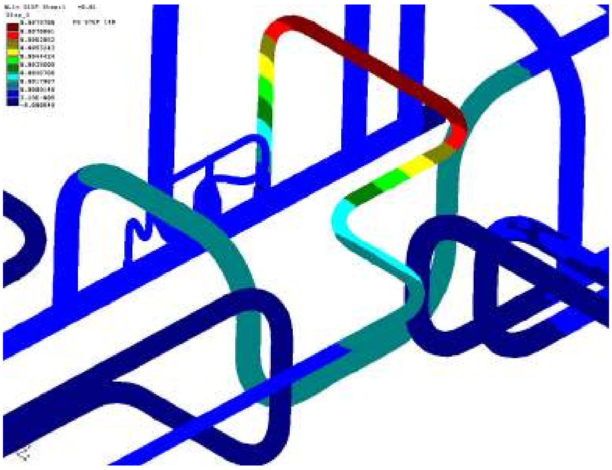

FIG. 12. Field of instantaneous response displacements

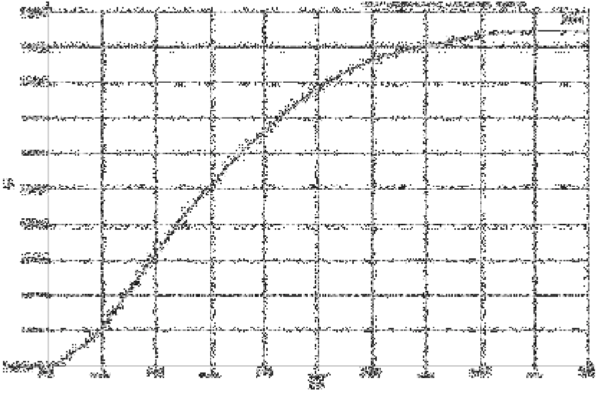

FIG. 13. Time history of axial displacement of the separated pipe end

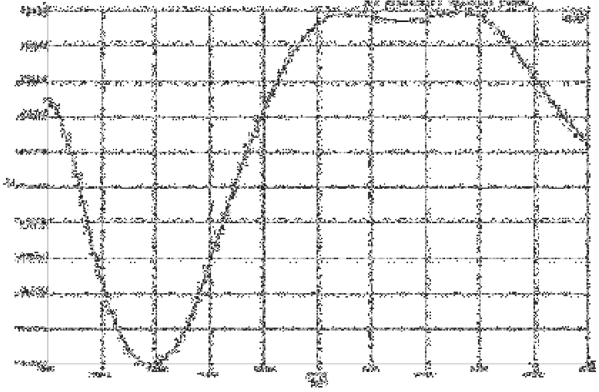

FIG. 14. Time history of axial displacement of the fixed pipe end

5. Seismic resistance analysis of ruptured piping

Special piping response analysis has been performed in order to assess the combined effect of earthquake event and pipe break (Ref.[4]). The analyzed system includes reactor coolant pump, steam generator and attached pipe branches (WWER-1000 NPP). A pipe whip restraint using axial viscous elements is located at the steam pipe - steam collector weld. The pipe whip restraint is provided with a protective tube limiting the lateral whip. Seismic motion of the containment base is described by acceleration time histories. The break in the weld is postulated to occur at the instant when the vibration of the system due to seismic excitation attains the highest level. The pipe break is assumed to be initiated by a random increase of the pipe operating pressure. The FEM-based computer program SYSTUS is used for the response analysis, taking into account large deformations and non-linear material properties of the model. The program library offers a special element, the stiffness and damping coefficients of which may be defined as dependent on the relative displacement and velocity of its end nodes, respectively. Such elements, inserted between shell elements modeling the steam pipe weld zone, are used to simulate the process of circumferential crack development leading to pipe break opening. The same finite elements are used to model the viscous elements of the pipe whip restraint. The performed response analysis has proved, that properly designed pipe whip restraint with a protective tube ensures the seismic resistance of a broken pipe, too.

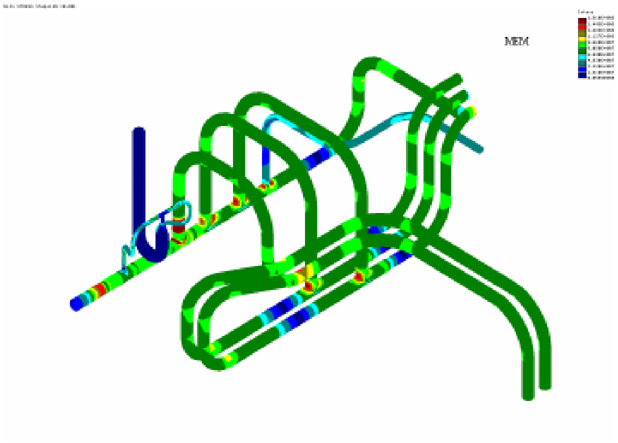

FIG. 15. Field of instantaneous stress intensities

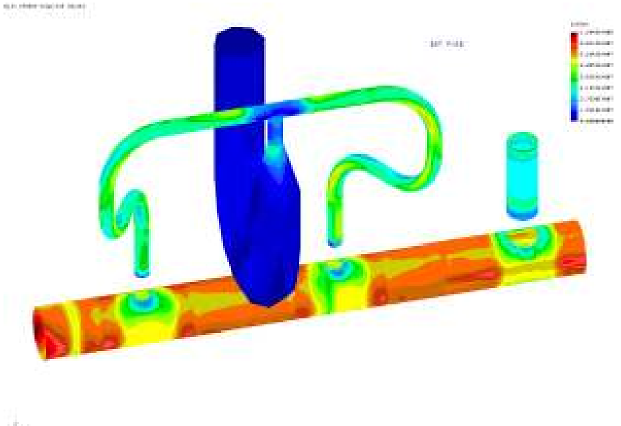

FIG. 16. Field of instantaneous stress intensities - detail

6. Conclusion

The performed analyses have shown, that modeling of the high energy piping system as a whole with supporting structures included represents the fundamental condition to get a reliable dynamic response to a pipe break event. Response analysis using separated piping system parts should be avoided.

Acknowledgements
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