ANALYTICAL INVESTIGATION OF PIPE WHIP RESTRAINTS AGAINST POSTULATED HIGH ENERGY PIPE RUPTURES

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ABSTRACT

This paper addresses results obtained during the project related with increasing of safety of VVER 440/230 type reactors of Kozloduy NPP. The scope of investigation is ensuring the safety related equipment located in Steam Generator’s Confinement (SGC) against postulated pipe ruptures of second circuit main steam piping systems.

After performing of preliminary PSA (Probabilistic Safety Assessment) for postulated pipe ruptures of main steam piping systems in SGC it was assumed that only the mechanical damage of equipment should be considered. The temperature and dynamic pressure effects of blowdown steam jet over surrounding equipment were assumed as not critical for the safety. With the performed PSA the postulated pipe ruptures were determined critical for the safety and on this basis significantly was reduced the total number of the design analyses.

The restraining of pipes whipping was done with two types of pipe whip restraining devices. Investigation of mounting locations of restraining devices was performed after free whip motion study, walkdowns for checking of collision with other equipment and pipelines analyses with the new devices in their mounting positions. The free whip analyses were performed as nonlinear time history analyses. In the design of pipes whip restrains nonlinear static and energy balance type of analyses were used.

Keywords: pipe rupture, whip restraint, impact mass, kinetic energy, nonlinear time history analysis.
1. INTRODUCTION

Current requirements for the nuclear safety of Nuclear Power Plants’ (NPP’) are based on a defense-in-depth philosophy considering the protection against postulated pipe ruptures by systematic evaluation approach. For the existing NPPs due to the complexity of the systems layouts and geometry of the rooms it is not possible to isolate the pipe systems with rupture potential. To prevent safety related equipment from impact effects of high or moderate ruptures new pipe restraints or barriers have to be designed and installed to the critical points of the piping systems.

High-energy piping is that one with operating pressure over 19.25 bar or temperature over 93.3°C. Piping systems that operate above these limits for a relatively short time (less than 2%) and preserve to perform their intended function, are classified as moderate energy piping systems. Piping systems classified as high or moderate energy systems are analyzed for postulated ruptures. Postulated ruptures are classified as circumferential breaks, longitudinal breaks, leakage cracks and through-wall cracks [1]. Each postulated rupture shall be considered separately as a single postulated initiating event. The type of rupture depends from the stress level and the ratio of axial and membrane stresses. If the geometry is complex and the simplified methods are not applicable, the detail finite element analyses or test have to be performed.

The locations of pipe ruptures are at terminal ends of the pressurized portion of the pipeline and at intermediate location with stress level over specified design criteria.

The damages after pipe rupture of high or moderate energy piping are from: mechanical impact, jet blowdown pressure, overall pressurization, environmental condition and flooding. After performing PSA analyses only mechanical impact effects from free whipping pipes were considered as important for nearby safety related equipment. The PSA analyses and the investigation of ruptured pipes motion trajectories (for example see Figure 6 and Figure 7) allow for significant reduction of the design efforts and the cost of purchasing and installing of new restraining devices and barriers.

2. EVALUATION OF PIPE WHIP AND IMPACT FORCES

2.1 Fluid forces

The shape and the value of jet force are conservatively evaluated according to [1]. The thrust force is assumed with constant value equal to maximum. For saturated steam (this project case) in steady state condition the jet force maximum is given by equation:

\[ T_{SS} = C_T P_0 A_E \]  

\[ \text{Eq. 1} \]

where,

- \( T_{SS} \) – steady state thrust force at time, \( t_{SS} \);
- \( t_{SS} \) – time to reach steady state;
- \( C_T \) – steady state thrust coefficient (\( C_T = 1.26 \) for typical high energy systems);
- \( P_0 \) – initial pressure in the source.

2.2 Evaluation of pipe whip

The methods for evaluation of pipe whip are:

Complete System Dynamic Analyses (CSDA) – a full dynamic time-history analysis, under which the equations of motion have to be evaluated with direct numerical integration method. Usually this method is the most time consuming and expensive. Because of complex geometry of the rooms and amounts of interactions with the nearby equipment, concrete and steel structures this method was used to predict the trajectories of the broken pipes in conjunction with the PSA analyses. During the detailed design of restraining devices and barriers this method was used to predict short distance motion trajectories and to precise location positions of the restraining devices and barriers.

Simplified Dynamic Analysis (SDA) – the same methodology as CSDA, with modeling of portion of pipe system.

Quasi-Dynamic Analysis (QDA) – series of CSDA of representative pipe systems analyses are tabulated or graphed. For a particular pipe system results are obtained with interpolation.
Energy Balance Analysis (EBA) – time dependency is not considered, constant thrust force is assumed. It shall be demonstrated that the system energy is absorbed during the kinematic motion. This method is mainly used for the design of restraining devices and barriers in the project. Details are described below.

Static Analysis – jet reaction force with appropriate considered amplification factor is applied statically. The evaluation of the amplification factors refers to CSDA or SDA methods.

3. DESIGN METHODOLOGY

The scope of the project was the analysis and design of restraining devices for high-energy pipe breaks of the secondary circuit in the Steam Generator’s Confinement of WWER 440/230 type reactors at Kozloduy NPP.

Design concept is focused on restriction of critical for safety free pipe whips. The selection of the critical pipe whips was made by preliminary PSA analysis. As an additional requirement the operator’s request is considered for preventing pipes disturbance under normal operation conditions when the new restraints are mounted. Also the metal control should not be restricted due to the mounting of the new restraints.

The assessment of pipeline – restraining device interaction as well as the design of restraining devices and their anchorages are based on Energy Balance method [1].

3.1 General assumptions

1. The jet force is assumed to be constant with a value equal to the maximum, calculated from the analysis of the jet stream.
2. The lateral deflection force is assumed 30% from the maximum value of the jet force.
3. Restraining devices (RD) are designed to have enough capacity to resist the full impact energy. No plastic work of the RD material or materials of anchors are allowed.
4. Due to the specifics of the energy balance analysis, the moment of maximum interaction between the pipe and RD is unknown. The calculated interaction forces of the first contact are increased with 10% for taking into account this uncertainty.
5. Due to the assumption for very short contact duration and the fully elastic behavior of the system it is assumed that the dynamic design strength of the mild structural steels is 80% from the ultimate static strength for the corresponding environmental temperature [1], [6]. The design strength of the high strength steels was assumed to be equal to the static strength for the corresponding environmental temperature.
6. The structures of restraining devices are designed to be compact to the maximum reasonable extent in order to minimize their influence on the normal operation of the respective pipelines (including free temperature deflection in operational conditions, changes of the pipes heat insulation, metal control, etc.). The number and the locations of the restraining devices are optimized for the same reasons.

3.2 Interaction forces

The interaction forces are determined on the basis of the equations of motion of undeformed body with single degree of freedom (SDOF). The active mass of whipping pipe was determined using the principle of equivalent kinetic energy. The active mass was evaluated with preliminary CSDA (see Figure 6 or Figure 7 as example). It is assumed a linear increase of the velocity with the time and corresponding constant acceleration in the different stages. The first stage is a stage of free motion of the body before the contact with RD. The second stage is a stage after the impact of the pipe with the RD (see Figure 5).

Stage 1 (free motion of the pipe before the contact with RD)

On the base of equations of motion of undeformed body with one degree of freedom was determined the initial parameters of the impact: added mass, velocity, acceleration, the time of free motion.

The time of free motion of the pipe till the contact with RD is:

\[ t = \sqrt{\frac{2.S \cdot m}{F}}, \text{s} \quad \text{Eq.2} \]

where:

\[ S \text{ [m]} \] – distance from original pipe location to RD;
\[ m \text{ [kg]} \] – added mass;
\[ F \text{ [N]} \] – thrust jet force;

The acceleration of motion is:
The velocity in the moment of the contact is:

\[
v = \sqrt{\frac{2SF}{m} \left[ \frac{m}{s^2} \right]} \quad \text{Eq. 4}
\]

**Stage 2 (after impact of the pipe with the RD)**

An equation of motion of undeformed body with total equivalent mass “m” was used. The undeformed body is supported by springs with equivalent strength “k” and has initial velocity “\(v_0\)”, which is the velocity in the moment of impact. Using the low for energy preservation it can be worked out an equation of motion of body in the moment of impact (contact):

\[
\frac{1}{2} k(P)x^2 - Fx - \frac{1}{2} m.v_0^2 = 0 \quad \text{Eq. 5}
\]

where:
- \(k(P) \, [N/m]\) – equivalent stiffness of the complete system (see Eq.7);
- \(F \, [N]\) – thrust jet force;
- \(P \, [N]\) – impact force (see Eq.6)
- \(m \, [kg]\) – added mass
- \(v_0 \, [m/s]\) – initial velocity in the moment of impact (see Eq.4);

The positive root of equation gives the maximum deformation of the complete system (CS) Pipe-RD-RCstructure. Multiplying the maximum displacement “\(x_{max}\)” and the corresponding stiffness “\(k(P_{max})\)” gives us the maximum impact force.

\[
P_{max} = x_{max} k(P_{max}) \quad \text{Eq. 6}
\]

It can be seen that the stiffness is a function of the impact force and vice-versa (see the non-linear diagram on Figure 3). With an aim to consider the real response of the complete system Pipe-RD-RC structure in the equivalent stiffness “\(k(P)\)” are taken into account the following factors: a) buckling and plastic work of the pipe and b) elastic stiffness of the RC structure. The RD was assumed as completely rigid. The deformations and stresses in the interacting elements are local. In general equation of motion (Eq.5) the plastic work of pipe is not included (it is taken into account considered only with its reduced stiffness). This gives additional safety factor for the developed design forces in the range of 1.10-1.20.

The task for determination of equivalent stiffness of CS includes determination of pipe wall stiffness under local loading (see Figure 1) and determination of local stiffness of RC structure (see Figure 4). The both stiffnesses are determined with incremental static FE analyses including material plasticity and large deflection effects. It was also possible to calculate the stiffness of RC structure with only one step (constant stiffness), due to the assumption of fully elastic behavior of this material. RC wall is relatively very stiff and respective displacements are very small.

The Force-Displacement diagram (see Figure 2) gives a realistic visualization of the pipe work. From small forces the behavior is linear elastic, followed by buckling, and post buckling - ideally plastic behavior.

The equivalent stiffness of CS Pipe-RC structure (wall) is calculated by scheme of two consecutively connected springs:

\[
k = \frac{k_1 k_2}{k_1 + k_2} \quad \text{Eq. 7}
\]

The stiffness of ruptured pipe system (the runs with both ends broken) is very small, considering the amounts of hangers and springs supports. The model analyses of the ruptured runs, which are not close to the terminal ends, show 1000 times smaller stiffness in the direction of impact than stiffness of pipe wall or RC wall. Practically only
the pipe wall has significant influence of calculated impact forces (the deviation from the equivalent stiffness is about 1%). It can be seen that equivalent stiffness is nonlinear and the solution of equation Eq.5 should be done only by iterations.

3.3 Complete System Dynamic Analyses (CSDA)

For evaluation of whipping pipes trajectories (without RD) and PSA assessment of the pipe rupture influence to the safety a full dynamic time-history analysis was performed. After the design of RD and their positioning it was checked the integrity of the ruptured pipe system. As design criteria for the integrity of the pipe system and supports, the level of plastic deformation and reaction forces in the spring and hanger supports was used (see Figure 12 and Figure 13).

The response of pipe systems subject to jet forces is characterized with relatively large deflections, compared with the dimensions to nearby equipment and RC walls. To consider the interactions with them their fragments are modeled (see Figure 9). Because of time consuming due to contact, plastic and large deflections effect the computer model of broken pipe system and nearby heavy interacting elements is tuned to be very economical. For modeling are used beam (pipe), elbow (pipe), tee (pipe), shell, contact and combined type finite elements.

For modeling of pipe segments are used FE (straight pipes and elbows) with capabilities to adobe: large deflections, material plastic behavior and internal pressure (see Figure 8 and Figure 12). The tee is modeled with elastic finite element. The model of pipe steel behavior is pure plastic (see Figure 10).

Contact problem is solved using surface to surface and point to surface contact elements depending of complexity of contact problem. The friction was modeled according to Coulomb friction model (see Figure 11).

The fragments of RC walls and heavy equipment (pressurizer) are modeled with elastic shell elements, which are covered with target contact plate elements.

The supporting system from springs and hangers are modeled with combined type finite elements, which can consider change of initial geometry and corresponding change in reaction forces.

4. CONCLUSIONS AND ACKNOWLEDGEMENT

The pipe response is very complex and has many interactions with a nearby equipment, steel and RC structures. In this study only heavy equipment and RC walls was considered (precise modeling will require significant modeling and computing efforts). Because of this CSDA analyses are performed only as benchmarks and engineering assessment (PSA and structural integrity assessment) of pipe systems response.

PSA analyses and carefully investigation of trajectories from CSDA of ruptured pipe systems allow significant cost reducing of design, purchasing and installing of new restraining devices and barriers (approximately 70% in this project).

For design purpose an Energy Balanced Analyses was used. The method combined with CSDA (for considering of added mass) gives reliable and simple results for design of RD. Initial parameters and assumptions for performing of EBA (velocity, acceleration, time of contact (impact), added / activated masses) are compared with CSDA analyses results, the coincidence is good.

This paper is in memory of our teacher and colleague Prof. Todor Karamanski who passed the way in the time of finalizing the referenced project work. This is an acknowledgement to Prof. Todor Karamanski’s huge scientific research work based on his unique common sense approach to the complex problems.

REFERENCES

Figure 1 Deformed shape of examined pipe run

Figure 2 Pipe Wall Force-Displacement diagram of examined pipe run

Figure 3 Pipe Wall Force-Stiffness Diagram of examined pipe

Figure 4 Deformed shape of RC wall under local loading

Figure 5 Steps of SDOF model motion
Figure 6 Top view of deformation scheme of pipe rupture at the terminal end close to the steam generator

Figure 7 Isometric view of deformation scheme of pipe rupture at the intermediate location close to a tee
Figure 8 General view of half Main Steam Line #6 after pipe rupture at the intermediate location

Figure 9 Main Steam Line #6 with nearby heavy equipment and fragments of RC walls
Figure 10 Work diagram of pipe steel

Friction Model

Figure 11 Coulomb friction model for contact problems used in the time history analyses
Figure 12 Plastic strains diagram due to jet force

Figure 13 Variation of reaction force in spring #13