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IMPACT OF RESTRAINED THERMAL EXPANSION ON NPP KRŠKO PRIMARY LOOP PIPING

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Original scientific paper
Mechanical analyses of the Krško NPP primary system piping subjected to the restrained thermal expansion due to insufficient pipe shim clearances are addressed in the paper. Reduction of clearance between a pipe and respective pipe restraints preclude free thermal expansion of the pipe system during the heat-up, thus causing a rise of excessive contact forces in the pipe - pipe restraint pairs. This results in a development of unfavourable strains and stresses both in pipes and restraints. A series of numerical simulations was performed which demonstrate sufficient strength resistance of the Krško NPP primary piping, while supports are much more susceptible and need careful engineering consideration.

Keywords: *finite element method, nuclear power plant, pipe restraint, piping, primary loop, thermal expansion*

Utjecaj ograničene termičke ekspanzije na primarni cjevovod Nuklearne elektrane Krško

Izvorni znanstveni članak
U ovom radu opisane su mehaničke analize primarnog cjevovoda Nuklearne elektrane Krško, koje obrađuju problem djelomično onemogućene termičke ekspanzije cjevovoda uslijed nedovoljnog razmaka među pločama ograničavača pomaka cijevi. Smanjenje razmaka između cijevi i pripadajućeg oslonca spriječava slobodno termičko proširenje cjevovoda tijekom zagrijavanja sistema. Time se prouzrokuju jake tlačne sile između cijevi i oslonaca, što se rezultira kao nepovoljno stanje deformacija i naprezanja i u cjevovodu i u potporama. Izvedene su serije numeričkih simulacija, koje potvrđuju dovoljnu čvrstoću primarnog cjevovoda Nuklearne elektrane Krško. Međutim, oslonci su puno više osjetljivi na opterećenja te vrste i stoga je za njih potrebno izvesti brižljivo konstrukcijsko razmatranje.

Ključne riječi: *cjevovod, metod konačnih elemenata, nuklearna elektrana, ograničavač pomaka cijevi, primarni krug, termička ekspanzija*

1 Introduction

The primary loop supports of the Krško Nuclear Power Plant (NPP) which is a Westinghouse two-loop Pressurized Water Reactor (PWR) type of nuclear steam supply system, were designed to meet two mutually exclusive demands: first, to allow free thermal expansion of the system during the heat-up, and second, to prevent excessive movement of loop components during eventual seismic and accidental events. This is achieved by means of snubbers and bumpers, the latter being shimmed during the hot test to a prescribed, usually very small clearance with respect to the primary equipment components.

During an eventual large Loss Of Coolant Accident (LOCA) the bumpers, which function as the Steam Generator (SG) lateral supports, and pipe whip restraints would experience extreme loads. Accordingly, they were designed mainly to limit the coolant loop displacements after an eventual double-ended guillotine break in the primary piping. But in the case of shimmed clearances that are too small, the pipe whip restraints actually represent a potential impediment for the loop thermal displacements, thus causing unexpected additional stresses even during normal operation.

The motivation for our work came out during the Krško NPP modernisation, when trying to clarify some dilemmas regarding the Leak-Before-Break (LBB) concept implementation. The crucial presumption of the LBB concept is that the leakage can be observed before a double-ended guillotine break of the pipe can occur. Consequently, the pipe whip restraints can be abandoned, because their only task is to prevent excessive movements of the broken pipe during LOCA, which would never happen according to the LBB concept. The opponents of this concept disagree with such explanation, especially, because they see no reason to remove the already installed security devices. But the answer of the LBB concept supporters is that the pipe whip restraints represent a potential danger for the system. Namely, the improper shimming (i.e. too small clearance) caused by a human error can affect negatively the stress state in the primary piping by the heat-up thermal expansion. They also claim that the probability of the improper shimming occurence is much higher than possibility of the LOCA, which only confirms their opinion about disassembling the restraints. With reference to the above contradictive views we try in our work to quantify the influence of the improper shimming on the Reactor Cooling System (RCS) primary piping.

To check the degree of influence that a restrained thermal expansion would have on the structural integrity, a series of numerical analyses was performed. For that purpose a finite element based numerical model of the two-loop cooling system, with all relevant structural components and displacement constraints being considered, was developed. The model was subjected to the loadings associated with the normal operating conditions of the coolant system (dead weight, pressure, temperature). The computational analyses were repeated several times, each time one of the pipe whip restraints is improperly shimmed, i.e. initial clearance is set smaller than prescribed by design. For each simulated restraint case the displacements of the primary piping, as well as the reaction forces in the components supports, were calculated.

Afterwards, with the piping support loads known, a detailed numerical model of the hot and crossover leg of the primary piping was used to calculate strains and stresses in the piping for each investigated case. Since the main concern of the work was focused on the investigation of the mechanical response of the structural system under normal operating conditions, the corresponding temperature and pressure field distributions of the coolant were assumed constant, as established at 100 % power. Therefore, all computational analyses were performed as static, but including a non-linear inelastic material behaviour.

2 Numerical Model

To treat strains and stresses in a pipe wall also for the case of lateral pipe loadings, i.e. pipe restraint forces, in a reliable and objective way, a detailed numerical model based on the Finite Element Method (FEM) is needed. The computational analyses were performed by using the FEM code Abaqus/Standard Version 5.8. In the model, S4 shell-type finite elements (4-node doubly curved general-purpose shell, finite membrane strain) were used, covering the hot and crossover leg of the primary piping, as shown in Fig. 1. The shape and size of the domains, denoted as A_1, A_2, A_3 and A_4 in Fig. 1, upon which the lateral forces F_1, F_2, F_3 and F_4 are acting, are determined according to the technical specification [1]. The forces are applied to the shell nodes in such a way that a stiff pipe restraint is simulated, i.e. all shell nodes in the same domain A_i are cinematically restrained to have the same displacement in a direction, perpendicular to the shim surface.

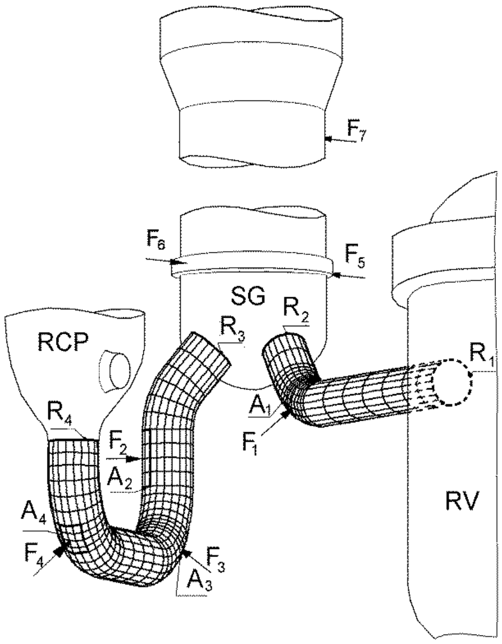

Figure 1 Hot and crossover leg of the primary piping modelled with shell elements

Primary loading on the RCS hot and crossover leg pipes arises from the weight and hydrostatic fluid pressure. Besides the primary loading, a very important part is due to secondary loads, such as thermal loads, terminal loads (i.e. the interaction loads at the pipe junctions with the large component primary equipment) and restraint loads at the pipe supports. With the exception of thermal loads, the mechanical analysis of the whole RCS is needed in order to identify the remaining two kinds of secondary loads. Therefore, a corresponding two-loop beam-type finite element model of the RCS was built (Fig. 2), containing also beam modelling of the concerned hot and crossover legs (Fig. 1) of the primary piping, which is highlighted by a thick line in Fig. 2. With respect to the shell-type model (Fig. 1), if used also in modelling of the whole RCS, the beam-type model (Fig. 2) is definitely less accurate. However, aiming to follow the analysis methodology [1] which is also approved in [3], the use of such a beam-type model is justified. Since the objective of the investigation is to consider the effect of reduced clearances of the pipe restraints, special attention should be paid to proper modelling of the pipe restraints, in order for the model response to be as accurate as possible. Because of that, our beam-type model has some capabilities, which cannot be found in a corresponding beam-type model in [1]. Among them is a possibility to simulate a geometric non-linear response, i.e. pipe restraints. The model is built of a variety of finite element types:

1) beam-type elements:
   a) B31 (2-node linear beam in space) used for the RCP (reactor cooling pump) and SG supports;
   b) PIPE31 (2-node linear pipe in space) used for all those components that are loaded with the internal pressure, such as the RV (reactor vessel), SG, RCP and all the secondary piping;
   c) ELBOW31 (2-node pipe in space with deformable cross-section, linear interpolation along the pipe) used for the primary piping;
2) other elements: springs, gaps, masses, rotary inertias and various connectors.

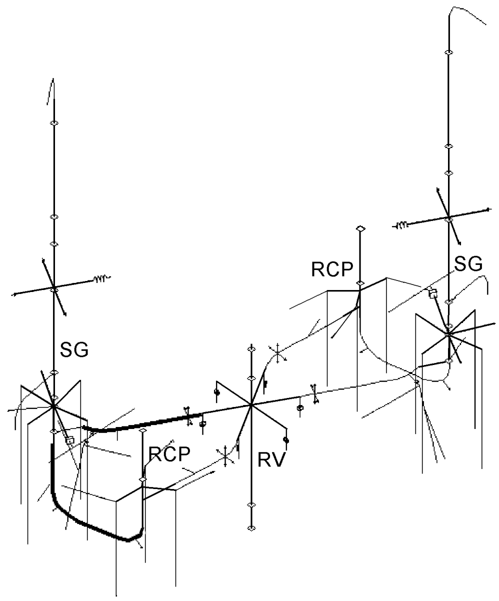

Figure 2 Two-loop reactor coolant system modelled with beam elements

Effects of the cross-section ovalization and warping modes of the pipe elbows deformation were taken into account by using elbow-type finite elements for pipes of the primary piping and prescribing corresponding pipe cross-section properties. Although the elbow finite elements include the warping and ovalization effects due to global bending, they cannot consider ovalization of the cross-section due to local bending, as provoked by an external lateral force acting on the pipe wall. From the computational analysis of the RCS (Fig. 2), in which all the mechanical and thermal loads characterizing normal operating conditions are considered, a response of the pipe system can be extracted.

To create a detailed model of the hot and crossover leg, substructuring of the RCS is applied. The extracted respective substructures are then modelled with the shell-type finite elements, and subjected to the corresponding boundary conditions, that have been identified by the beam-type model simulation. Displacements and rotations of the points that represent piping terminals at the RV, SG and RCP nozzles, are transformed into prescribed displacements and rotations of the respective pipe cross-section planes, in Fig. 1 denoted by R_1, R_2, R_3 and R_4. In addition, the pipes are loaded with external forces F_1, F_2, F_3 and F_4, which have been computed from the beam-type model as contact forces due to pipe restraints. Additionally, the pipes are loaded with a uniform temperature and internal pressure distribution, according to the normal operating conditions, as defined by [2]. Thermo-mechanical properties of the primary piping, which is made of SA 351 CF8A, are obtained from [3].

2.1 Analysis Methodology

To evaluate the impact of a reduced shim clearance, strains and stresses in the hot and crossover leg of the primary piping are computed in accordance with the proposed two-model approach, following a numerical strategy that is summarized in the following three steps:

Step 1 - Imposition of initial clearance at the pipe restraints. All pipe restraints except one are shimmed to the values, prescribed by design or by measurement during the hot functional test [1], while clearance at the remaining pipe restraint is numerically set to an arbitrary value, which is lower than the design or measurement prescribed one. By such a supposition the primary pipe would, very probably, be impeded from expanding freely as the coolant temperature increases to the normal operating state. In consequence stresses of permanent character that were not considered by the design would appear during normal operating of the power plant.

Step 2 - Mechanical analysis of the whole RCS according to the beam-type model. Since gaps and spring elements are included in the beam-type model of the RCS, a realistic system response to the imposed pipe restraints clearances can be obtained. To this end the pipe whip restraints are modelled with different types of elements, to which proper stiffnesses should be prescribed. The stiffness of the support being known, it remains to estimate the ovalisation stiffness of the pipe. For that purpose the pipe submodels corresponding to a particular pipe-pipe restraint pair were built, including in the beam-type model an element that connects the pipe centre-line with a gap and has thus ability to stretch due to radial thermal expansion of the pipe and to contract due to external lateral load on the pipe circumference as shown in Fig. 3.

From the computed analysis results the mechanical response data, indispensable for the subsequent detailed substructure analysis, are extracted. This discrete data set consists of displacements and rotations of the RV, SG and RCP nozzles, displacements of the pipe centre-line at the pipe restraint locations, displacements of individual pipe restraints, and finally, reaction forces at the pipe restraints.

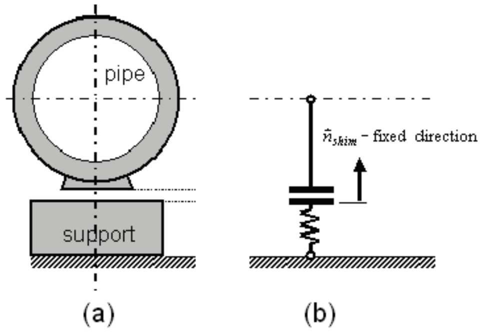

Figure 3 Pipe-whip restraint; (a) sketch, (b) beam-type model

Step 3 - Mechanical analysis of the piping substructure according to the shell-type model. The shell-type models of the hot and crossover leg are considered in accordance with the mechanical response of the RCS, which has been obtained by the beam-type model. Consistency and physical objectivity of the substructure response with regard to the previously computed RCS deformation field implies above all the imposition of the displacement compatibility at the substructure interface boundary. Boundary conditions that are applied to the substructure model are therefore given in terms of the prescribed displacements and rotations of the pipe end cross-sections, available from one part of the discrete data set, which has been formed at the end of the previous step. Also contact forces F_1, through F_4, resulting from the restrained thermal expansion of beam-type model must be applied to enforce the static equivalence of shell-type model. It should be emphasized that the vessels' nozzles (RV-outlet, SG-inlet, SG-outlet, RCP-inlet) were also modelled with shell elements (not shown in Fig. 1) to improve the shell-type model solution. The substructure boundary conditions are strongly affected by the different material properties and wall thicknesses in the nozzles and pipes. The material properties of the nozzles are nonlinear and temperature dependent (SA508 for RV-outlet, SA216 for SG-inlet and SG-outlet, SA351 for RCP-inlet). The material data for all materials used in the analysis are given in [3]. Results of this detailed analysis yield both the stress and strain fields, as well as the displacement field in the pipes. From the latter the pipe wall indentation can be evaluated.

To improve the accuracy of the numerical models, the following procedure was repeated until convergence criteria were fulfilled:

1) The pipe in the shell-type model is loaded with the whip restraint reaction force and subjected to the terminal displacements and rotations as obtained from the beam-type model;
2) The centre-line displacements in both models are compared. Also the indentation of the pipe in the shell-type model is compared with the contraction of the connector element in the beam-type model;
3) If the discrepancies between the monitored quantities are too large, the stiffness of the connector element between the pipe centre-line and respective gap in the beam-type model (Fig. 3), which represents the pipe's ovalisation stiffness, is adequately adjusted, and the

analysis is repeated. If the discrepancies are acceptable, the procedure is terminated.

The effect of the reduced shimming can be seen through the developed deformation patterns, which are schematically shown in Fig. 4. The imposition of contact at a restraint due to reduction of the respective shimming clearance (label Δ_{RC} in Fig. 4) causes all structural components in contact to displace with respect to the non-contact configuration. The magnitude of enforced overlapping of the respective pipe - pipe restraint pair equals the difference between the imposed change of clearance Δ_{RC} and prescribed clearance at normal operation Δ_{gap}. This overlapping is partly compensated through the displacements of the pipe's centre-line Δ_{axis} and pipe's restraint $\Delta_{support}$, and partly also through the pipe wall indentation Δ_{indent}. The first effect can be attributed to the RCS global deformation, the second to the pipe restraint support structure deformation, while the latter is exclusively a result of purely local pipe wall deformation.

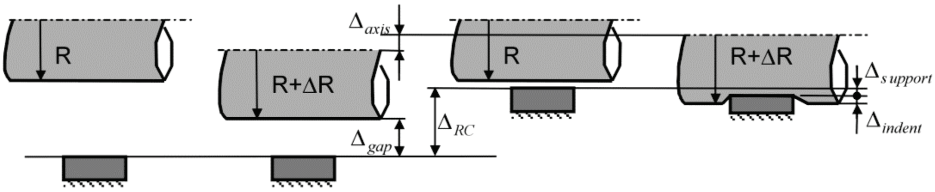

Figure 4 Displacement pattern for various shim clearances: (a) cold shutdown position at prescribed shim clearance, (b) normal operation position at prescribed shim clearance, (c) cold shutdown position at reduced shim clearance and (d) normal operation position at reduced shim clearance

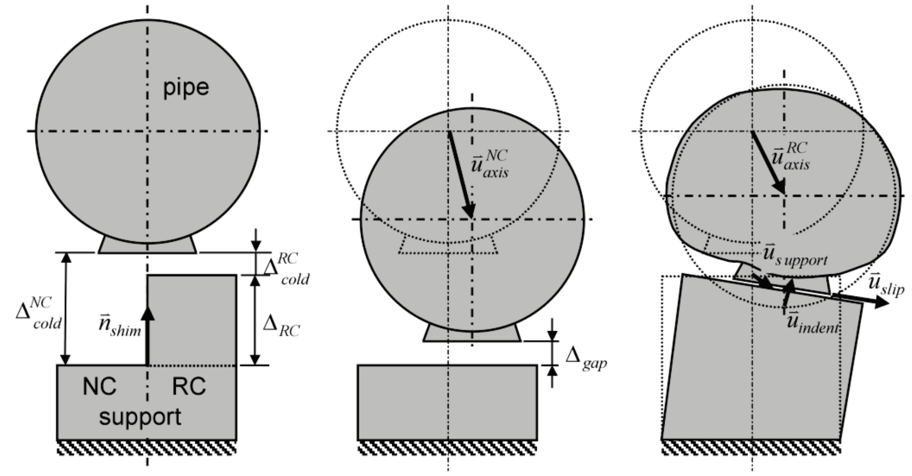

Figure 5 Displacement vectors: (a) initial position of pipe (NC-design prescribed, RC-reduced clearance), (b) operation at design prescribed clearance and (c) operation at reduced clearance

While the prescribed and reduced clearances Δ_{gap} and Δ_{RC} are measured in the direction $\vec{n}_{shim}$ which is perpendicular to the initial position of the shim plate, the actual directions of the respective displacement vectors are oriented independently and arbitrarily in space, as schematically shown in Fig. 5. The described distances of interest, Δ_{axis}, $\Delta_{support}$ and Δ_{indent}, are thus projections of the respective displacement vectors on the direction vector $\vec{n}_{shim}$, which gives:

$$\begin{aligned} \Delta_{axis} &= \left| \left(\vec{u}_{axis}^{NC} - \vec{u}_{axis}^{RC} \right) \cdot \vec{n}_{shim} \right|, \\ \Delta_{support} &= \left| \left(\vec{u}_{support} + \vec{u}_{slip} \right) \cdot \vec{n}_{shim} \right|, \\ \Delta_{indent} &= \left| \vec{u}_{indent} \cdot \vec{u}_{shim} \right|, \end{aligned} \tag{1}$$

where NC and RC refer to normal, i.e. design prescribed, and reduced clearance operation, respectively. Finally, with the imposed clearance reduction Δ_{RC} the compatibility equation

$$\Delta_{RC} = \Delta_{gap} + \Delta_{axis} + \Delta_{support} + \Delta_{indent}, \tag{2}$$

must be fulfilled.

3 Results of numerical simulations

Because improper shimming analysis was not considered in an original analysis of the RCS [1], such an analysis belongs to the so-called beyond the design basis (BDB) analyses, where codes and exact instructions of how to conduct an analysis are not set yet. Thus we had no rules, nor previous knowledge about the influence of the pipe restraint clearance reduction. Therefore the numerical model was built flexible enough to allow imposition of any reasonable value of reduced clearance. Being aware that in real circumstances lessening of clearances with respect to those specified by the design (listed in the rightmost column of Tab. 2) comes out mainly as a result of inaccuracy in the shimming process [4], the clearance reduction should not be greater than several millimetres, to remain realistic. Eventual gross reduction of clearance is a pure consequence of large errors during heat-up (blocked shims, etc.) and is not covered by this investigation. Accordingly, lessening of 5 mm as a maximal value of clearance reduction is adopted in our numerical analyses.

Simulation of four cases was performed with four restraints being subject to change in clearance, one per case. The considered restraints set consists of one restraint at the hot leg elbow, one restraint at the crossover leg vertical run and two restraints at the crossover leg 90° elbows. In each case a clearance reduction of 5 mm on a single pipe restraint is assumed, leaving clearances at all other restraints at their prescribed design values. At the RV inlet and outlet nozzles pipe whip restraints are mounted as well. These restraints are shown in Fig. 2 as cross-like structure attached to the primary piping in the vicinity of RV supports. However, prescribed clearances of these restraints are big (from 10 to 55 mm), compared to other clearances (Tab. 2). Thus an eventual reduction of clearance within the assumed range of 5 mm would not affect the mechanical state of the RCS; therefore variations of these clearances are not considered in our work. Some results of the performed mechanical analyses are listed in Tabs. 1 ÷ 4, with numbering of the restraints following labels 1 ÷ 4, as given in Fig. 1.

Impact of the assumed shim clearance settings on the primary piping and SG supports can be seen from Table 1, in which the corresponding results are tabulated. As expected, we find that a reduction of shim clearance on a single restraint can induce huge reaction forces not only at this particular support, but also on other restraint supports. In addition, as it is the case of clearance reduction on the crossover leg, some of the lateral SG restraints may become active, too (forces $F_5 - F_7$ in Fig. 1).

Table 1 Primary piping and lateral SG support forces at 5 mm reduced clearance of shims

Clearance reduced at pipe restraint No.	Pipe restraint force / kN				SG lateral support force / kN		
	F_1	F_2	F_3	F_4	F_5	F_6	F_7
1	3657	0	0	0	0	0	0
2	0	1438	407	59	665	0	0
3	0	0	3972	3396	0	214	194
4	0	0	3011	5157	721	0	154

Table 2 Primary piping and supports displacements (1) at 5 mm reduced clearance of shims

Clearance reduced at pipe restraint No.	Pipe centre-line displacement u_{axis} / mm	Pipe wall indentation u_{indent} / mm	Pipe restraint displacement $u_{support}$ / mm	Prescribed clearance at normal operation / mm
1	1,868	0,985	1,572	0,8
2	2,164	0,465	0,042	2,4
3	4,453	1,285	0(2)	0,1
4	3,411	1,667	0(2)	0,1

(1) Absolute value of displacement vectors given (not their projected values in the clearance reduction direction), therefore, the sum of all displacement contributions + prescribed clearance can be greater than imposed 5 mm overlapping.
(2) Concrete support structure not modelled, thus support considered rigid.

In Tab. 2 the magnitudes of displacement vectors that we have defined in the previous section are tabulated for the shim clearance cases considered. With the clearance reduction in our investigation being fixed, the major factor influencing the mechanical state at a particular restraint is the size of overlapping, which is clearly seen also from Tabs. 1 and 2. But, with the overlapping being given, the intensity of the resulting contact force depends first of all on the respective global and local flexibilities. While local flexibility of the pipe wall and global flexibility of the pipe restraint is rather constant, this is not true for the flexibility of the piping at the considered restraint. In addition to the inertia properties of the pipe's cross-section, the global flexibility of the piping is determined directly by its layout, and, indirectly, by the stiffness of the large component primary equipment (RV, SG, RCP) to which it is connected. Finally, the flexibility to be used at the considered restraint location must take the spatial dependence of the piping flexibility into account (compare responses at restraints No. 3 and No. 4 in Tab. 2). It is for all these reasons that results, tabulated in Tab. 2, need careful background inspection, if general conclusions are to be drawn.

In the sequel, values of equivalent Mises stress and equivalent plastic strain at inner and outer surface of the pipe wall for 12 critical points on the hot and crossover leg of the primary piping are listed in Tab. 3. The positions of the respective points are shown in Fig. 6.

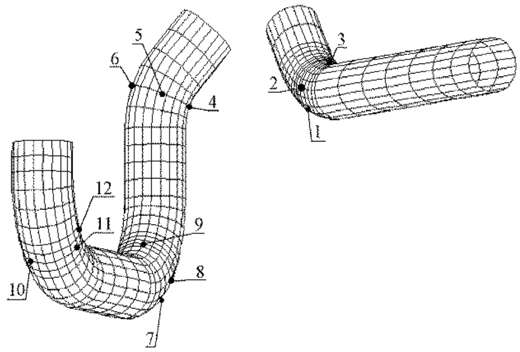

Figure 6 Position of critical points on hot and crossover leg

In Tabs. 3 and 4, the slash symbol "-" is used to denote that the magnitude of respective physical quantity for a particular point does not differ significantly from that established at normal operating conditions with no reduction of shim clearance. That magnitude is therefore not included in the table. From Tab. 3 it can be seen that stresses at some points exceed the elastic limit; however, the magnitude of the resulting plastic strain is small, almost negligible compared to the ultimate plastic strain, which is estimated to the value of 0,25. Considering this evidence a conclusion can be made, saying that even relatively large (5 mm) inadvertent reduction of shim clearance does not result in critical increase of stresses in the primary piping.

Table 3 Equivalent stress and equivalent plastic strain of primary piping wall at 5 mm reduced clearance of shims

Clearance reduced at pipe restraint No.	Critical point No. (Fig. 6)*	Inner pipe wall surface		Outer pipe wall surface	
		σ_{eq} / MPa	ε_{eq}^{pl} / -	σ_{eq} / MPa	ε_{eq}^{pl} / -
Normal operating conditions (prescribed clearances)	1	87	0	71	0
	2	77		122	
	3	123		110	
	4	125		130	
	5	107		112	
	6	96		100	
	7	80		80	
	8	90		103	
	9	117		112	
	10	86		74	
	11	92		93	
	12	127		119	
1	1	159	0,000295	130	0
	2	-	0	153	
	3	134	0	-	
	4 ÷ 12	-	0	-	
2	1 ÷ 3, 6 ÷ 12	-	0	-	0
	4	154		-	
	5	-		142	
3	1-6	-	0	-	0
	7	164	0,000118	154	0,000007
	8	-	0	150	0
	9	144	0	-	0
	10	164	0,000118	130	0
	11	-	0	140	0
	12	155	0	-	0
4	1 ÷ 6	-	0	-	0
	7	164	0,000080	113	0
	8	-	0	150	0
	9	160	0	-	0
	10	165	0,000418	166	0,000543
	11	-	0	164	0,000005
	12	148	0	-	0

* Yield stress at Hot Leg temperature (points 1 ÷ 3): $\sigma_Y(=R_{p0,2})$(SA351, 325 °C)=158 MPa,
at Crossover Leg temperature (points 4 ÷ 12): $\sigma_Y(=R_{p0,2})$(SA351, 287 °C)=164 MPa

Table 4 Support forces* on RCS elements at 5 mm reduced clearance of pipe restraint shims

			Forces in kN, – compression, + tension			
			RV support tangential force	SG column	RCP column	RCP tie rod
Prescribed clearances	Normal operation		–24, +45	–1236	–481	0
	Faulted conditions [5]		–2762	–1413	–1119, +1747	–200, +3543
	SSE [5]		±1651	–3453, +1365	–1194, +1053	–779, +827
Clearance reduced at pipe restraint No.	1	Normal operation	–507	+755	-	-
	2		–321	–274	-	-
	3		–477	+205	792	+578
	4		+435	–488	–292, +1667	–537

* Envelope of forces, acting on a particular RCS element

Although the change of the stress field in the primary piping, resulting from the imposed reduced shim clearance, is relatively small (but not negligible), the influence of a restrained pipe on other RCS components can be large. Here again, the global flexibility of the piping plays an important role in transferring the effect of the contact force at a pipe restraint to the connecting nozzles. As seen from Tab. 4, in which forces acting on the RV, SG and RCP supports are listed, rather extensive forces can result. In order to obtain better insight on the impact the reduced shim clearance has on these supports, three rows are added in the table. These rows contain the magnitudes of the reaction forces at three operation modes of the RCS (Normal Operation, Faulted Conditions – without large LOCA and safe shutdown earthquake - SSE) [5]. Since normal operation is considered in all reduced clearance analyses, a direct comparison with Normal Operation row is available. Indeed, quite a different bearing pattern can be recognized when thermal expansion of the primary piping is impeded. Some compressively loaded support members become loaded even in tension, if the shim clearance is reduced, which is seen from Tab. 4.

4 Summary and Conclusions

In view of quantifying the effect of restrained thermal expansion on the RCS structural integrity, numerical simulations of heat-up of the Krško NPP under imposed shim clearance reductions have been carried out and the corresponding mechanical responses of the RCS evaluated. A 5 mm reduction of the shim clearance has been applied at four pipe restraints of one loop of the primary piping separately, while clearances of the restraints on the second primary loop have remained unchanged. Reviewing the analyses results, the following conclusions can be drawn:

1) Primary piping stress state: In the worst case, which is the reduction of shim clearance at pipe restraint No. 4 (under the 90° elbow on crossover leg, RCP side), the maximal equivalent stress exceeds the actual yield stress by 1,2 % (σ_{eq}=166 MPa, $\sigma_Y(=R_{p0,2})$(SA351; 287 °C)=164 MPa). The size of the plastically deformed area of the pipe wall is small, with the amount of equivalent plastic strain being almost negligible (0,00055). It is worth noting that, if the restraint clearance is as designed, the maximal equivalent stress reaches 78 % of the yield stress. This clearly proves that the above evidenced increase of stresses in the pipe is mainly due to indentation of its wall.

2) Pipe restraint support forces: The greatest lateral force acting on the pipe wall appears in the case of clearance reduction on restraint No. 4. The considered case is, in fact, among the investigated cases, the most severe one. This is because of the largest overlapping and impossibility of the restraint support to displace (the support lies directly on the concrete wall of the reactor building structure which is assumed rigid), but obviously, also because of the increased piping stiffness at this restraint. The latter statement can be confirmed by comparing the considered deformation pattern with that of restraint No. 3 in Tab. 3. Also worth mentioning that the magnitude of 5157 kN of the considered force exceeds significantly the magnitude of forces owing to upset, emergency and faulted conditions (except large LOCA), acting on the same restraint in case of no shim clearance reduction [5].

3) Influence of reduced clearance on the components of RCS: According to Tabs. 1, 2, 3 and 4 the greatest influence on the RCS response during heat-up is manifested in case of reductions of shim clearance on 90° elbows pipe restraints on the crossover leg, reasons for this being already explained above. Since due to relatively large ovalization rigidity of the pipe, local effects in the form of pipe wall indentation are not greatly developed, and the contact loading effects are transferred from the respective restraint through the pipe to the rest of the RCS to a rather large extent. In consequence, the RCS support members manifest quite large forces in the supports, actually in the magnitude of SSE support forces. Moreover, the character of the resulted forces can change from compressive to tensile or vice versa. In this context, strength of elements, joining the compressive supports (bolts, nuts, bearings), should be thoroughly checked, while tensile support members should be inspected against buckling.

In our investigation there was no intention to state any general acceptance criteria about shimming tolerance, but to investigate two contradictory theses of the LBB concept that were described in the introduction. The main conclusion is, that because of shimming error, the stress state in pipes is subject to change, but the rate of stress increase is surprisingly small compared with the rate of support reaction forces enlargement. Therefore, we disagree with the thesis of the LBB concept supporters, that even a small error in the whip restraint clearance can induce a catastrophic damage of the pipe, maybe even a break of the pipe during heat-up. The presented analyses, with 5 mm of the clearance reduction imposed, show that the pipes can stand even large clearance error during heat-up. However, on the other hand another insidious property of the RCS was discovered: because of the sufficient rigidity of the primary piping the influence of the improper shimming is spread further to the main RCS components and their supporting system. In the stress analyses [5], where several static and dynamic loading cases had been computed in accordance with design specifications (no improper shimming assumed), it was found out that the RCS is supported very well both statically and dynamically in all cases. But, if the system is subjected to a reduced clearance, then the contact loading effects are transferred from the pipe to the other RCS components and the following consequences are expected according to our investigations: the components are no longer at their prescribed positions and are slightly inclined and thus lean against the other bumpers, where during normal operation no contact should occur. The secondary effect of such additional contacts is a change of the natural frequencies of the system, what has direct influence on the dynamic response, i.e. displacement amplitudes and peak stresses during earthquake. Furthermore, if the effect of the improper shimming on the pipes is low, errors need to be compensated in the RCS components, especially at their nozzles, which are one of the most critical parts of the components. To summarize, although we disagree with the thesis, that pipes will break during the heat-up if the clearances are reduced, we cannot assure without any inspection of clearances, that leaving the whip restraints as they actually are has no negative effect on the system. The main argument for such a statement is that reduction of the clearance at the whip restraints is not assumed in the design specifications, and therefore it is neither considered in any other project calculation of the NPP. Also, having a predicted response of the system to such an event only for the heat-up thermal expansion, but not during other transients (normal, upset, emergency, faulted condition), it is our opinion, that it is not reasonable to leave the possibility of such an error to occur. Therefore, if the whip restraints are not removed, their clearance should be controlled to ensure that the clearance is not too small. But, if the controlling process is abandoned, the problem should be reconsidered very carefully, with further calculations and analyses of the system response for all the transients and for many assumed reduced clearances needed.

5 Epilogue

In the year 2003 LBB concept was approved for Krško NPP, leading to the significant design load changes. Large LOCA was abandoned from mechanical analyses of primary piping (although it remains as a postulated event for other types of analyses), thus primary pipe whip restraints became obsolete and were removed from the primary piping system.

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7 List of Abbreviations

BDB – Beyond the Design Basis
LBB – Leak Before Break
LOCA – Loss of Coolant Accident
NC – Normal Clearance (design prescribed)
NPP – Nuclear Power Plant
PWR – Pressurized Water Reactor
R – Pipe terminal
RC – Reduced Clearance (improper shimming)
RCP – Reactor Coolant pump
RCS – Reactor Cooling System
RV – Reactor Vessel
SG – Steam Generator
SSE – Safe Shutdown Earthquake

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