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Response of the Steam Generator VVER 1000 to a Steam Line Break

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ABSTRACT

Dynamic effects of a steam line break in the weld of the steam pipe and the steam collector on the steam generator system are analyzed. Modelling of a steam line break may concern two cases. The steam line without a restraint and the steam line protected by a whip restraint with viscous elements applied at the postulated break cross-section. The second case is considered.

Programme SYSTUS offers a special element the stiffness and viscous damping coefficients of which may be defined as dependent on the relative displacement and velocity of its nodes respectively. A circumferential crack is simulated by a sudden decrease of longitudinal and lateral stiffness coefficients of these special SYSTUS elements to zero. The computation has shown that one can simulate the pipe to behave like completely broken during a time interval of 0,0001 s or less. These elements are used to model the whip restraint with viscous elements and viscous dampers of the GERB type as well.

In the case of a whip restraint model the stiffness coefficient–displacement relation and damping coefficient – velocity relation are chosen to fit the given characteristics of the restraint. The special SYSTUS elements are used to constitute Maxwell elements modelling the elasto-plastic and viscous properties of the GERB dampers applied to the steam generator.

It has been ascertained that a steam line break at the postulated weld crack between the steam pipe and the steam generator collector cannot endanger the integrity of the system even in a case of the absence of a whip restraint effect.

KEY WORDS: High energy pipeline, hydrodynamic forces, modelling of a circumferential crack, modelling of a whip restraint, non-linear whip dynamic analysis

INTRODUCTION

Safety Issues and Their Ranking for WWER-1000 Model 320 Nuclear Power Plants in the review of internal hazards makes mention on the occurrence of internal hazards resulting from high energy pipe breaks. The dynamic effects of high energy pipe breaks, such as pipe whips and jet forces due to the sudden release of liquids and steam, could lead to failure of safety related equipment [1].

The break in the weld of the steam pipe and the steam generator collector is postulated to occur. The pipe rupture is assumed to be initiated by a random increase of the pipe internal pressure.

Let us consider the postulated circumferential crack cross-section to be protected by a whip restraint with visco-plastic absorbing elements [2]. This whip restraint enables to limit both the longitudinal and lateral displacements.

The finite shell element models of the steam generator collector and of the steam pipeline are joined by special SYSTUS elements 1602 inserted between the cross-sections assumed to be separated by a circumferential crack (Figure 1). The whip of the pipeline is described by the response to a sudden uncoupling of the assumed parts of the model.

The system is treated as non-linear due to variable visco-elastic behaviour of whip restraint absorbing elements and due to the whip restraint elastic constraints with gaps imposed on the relative lateral motion of the uncoupled pipe cross-sections. Both these non-linearities are modelled by SYSTUS elements 1602.

SHELL MODEL OF THE SYSTEM

The finite element model of the system is shown in Fig. 1. The model consists of the following parts:

Steam generator – SG
Steam collecting legs, collector, steam line till penetration - SL
Reactor coolant pump (simplified) – RCP
Primary pipeline hot leg - HL

Primary pipeline cold leg - CL

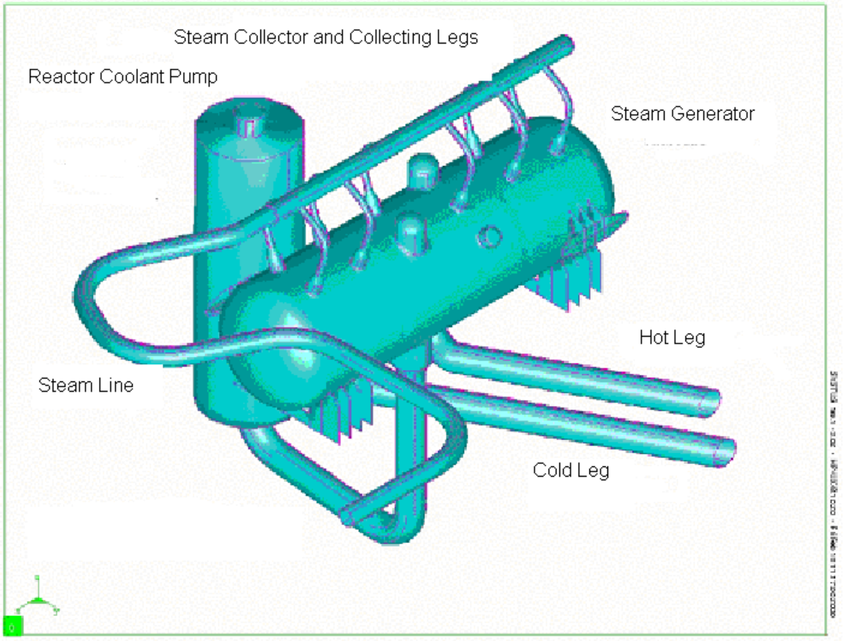

Fig.1 Components of the analyzed system

The steam pipeline is supported by elastic supports and build in the containment wall penetration.

HYDRODYNAMIC FORCES

Resultant external force **F** acting on a pipe section including a fluid inside of a control surface is equal to a momentum time derivative of the system

$$\mathbf{F} = \int_V \frac{d}{dt}(\rho\mathbf{c})dV + \int_A \rho\mathbf{c}(\mathbf{c}\circ\mathbf{n})dA \, . \tag{1}$$

Here ρ is the fluid density at a point, where the fluid velocity vector is **c**. A fluid domain of a volume V, to which the principle of momentum is applied, is given by a control surface which bounds the pipe segment on its internal surface and the input and output cross-sections.

The first integral in the volume V represents for a linear momentum time rate change in the respective fluid domain volume. The second integral on the surface A of the fluid domain describes a time rate change of the momentum due to input and output of the flowing fluid. Here **n** the unit vector of the external normal of a control surface element and $\mathbf{c}\circ\mathbf{n}$ the scalar product of a velocity vector and the unit vector of the external normal.

A fluid in the control surface is acted upon by the resultant external force composed of a resultant pressure force on the control surface and of a volume force due to the self weight or an inertia force. Let use denote **R** resultant reaction of the pipe on the fluid, A_{vst} the input cross-section area, A_{vys} the output cross-section area, p the pressure on a respective area element. When neglecting the fluid self weight, there is

$$\mathbf{F} = \mathbf{R} - \int_{A_{vst}} \mathbf{n}p\,dA_{vst} - \int_{A_{vys}} \mathbf{n}p\,dA_{vys} \, . \tag{2}$$

The resultant reaction is of the same magnitude as a force $\mathbf{F}_d$ representing the dynamic effect of the fluid on the pipe but of the opposite direction. Eqs.(1) and (2) yield

$$\mathbf{F}_d = -\left[\int_V \frac{d}{dt}(\rho\mathbf{c})dV + \int_A \rho\mathbf{c}(\mathbf{c}\circ\mathbf{n})dA + \int_{A_{vst}} \mathbf{n}p\,dA_{vst} + \int_{A_{vys}} \mathbf{n}p\,dA_{vys}\right]. \tag{3}$$

According to [3] it is admissible to neglect the transient process of the fluid flow variation when a pipeline is broken.. Thus we may assume the fluid flow to be stationary and the pressure p_{vst} in the input cross-section A_{vst} and the pressure p_{vys} in output cross-section A_{vys} as constant. The Eq. (3) may be arranged by means of the barometric pressure p_o to a form

$$\mathbf{F}_{db} = -\int_A \rho\mathbf{c}(\mathbf{c}\circ\mathbf{n})dA - \mathbf{n}_{vst}(p_{vst}-p_b)A_{vst} - \mathbf{n}_{vys}(p_{vys}-p_b)A_{vys}\,. \tag{4}$$

In case of a one dimensional flow the velocities $\mathbf{c}_{vst} = -\mathbf{n}_{vst}\, c_{vst}$ in the input area A_{vst} and the $\mathbf{c}_{vys} = \mathbf{n}_{vys}\, c_{vys}$ in the output area A_{vys} are constant so that

$$\mathbf{F}_{db} = \mathbf{n}_{vst}\rho c_{vst}^2 A_{vst} - \mathbf{n}_{vys}\rho c_{vys}^2 A_{vys} - \mathbf{n}_{vst}(p_{vst}-p_b)A_{vst} - \mathbf{n}_{vys}(p_{vys}-p_b)A_{vys}\,. \tag{5}$$

The problem of a fluid flow out of a broken pipe may be simplified by the assumption of hydrodynamic forces corresponding to a stationary flow out state [3].

In case of a sudden full opening of a short flow out tube the following conservative approximation [3] according to Fig. 2 is admissible. The force F_d is denoted as T. In case of a sudden full opening of a long flow out tube friction losses are considered. The comparison of the probable actual thrust with a recommended conservative approximation [3] is shown in Fig. 3.

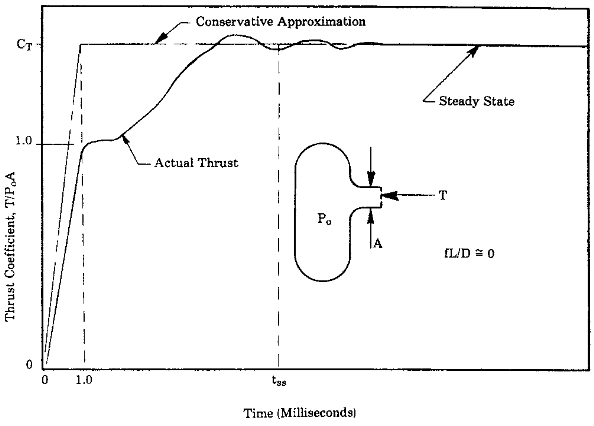

Fig. 2 Short flow out tube

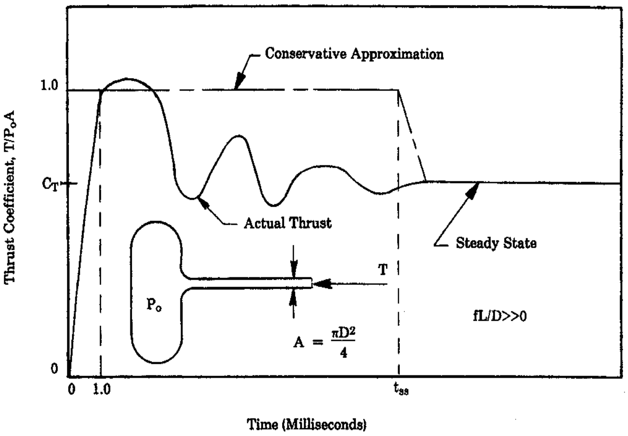

Fig. 3 Long flow out tube

PIPELINE BREAK AND WHIP RESTRAINT MODEL

To model a break up of the steam pipe twelve special elements SYSTUS 1602 are used. They are inserted in an artificial gap between the models of the steam collector and the steam pipeline. These elements join corresponding nodes of the shell models.

The stiffness-elongation relation of an average element corresponding to the situation at a time of 3 s is shown in Fig. 4. Till the relative nodal displacement of 0,107mm there is k_x = 15,65 GNm^{-1}. The lateral stiffness coefficients have the same characteristics. Their magnitudes are $k_y = k_z$ = 5 GN/m.

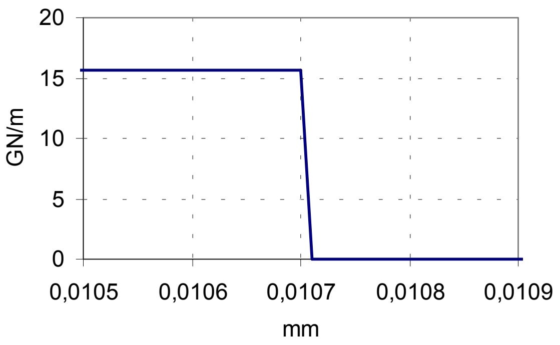

Fig. 4 Break element 1602 stiffness

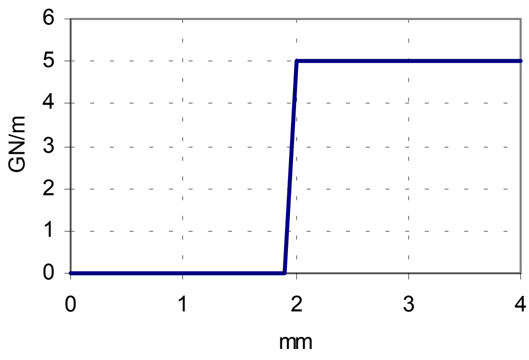

Fig.5 Lateral element 1602 stiffness

The whip restraint with viscous elements [2] protects the steam line at the cross-section of its postulated break. Elastic constraints with gaps of 2 mm are introduced in a lateral direction by the whip restraint between the collector and the steam line pipe (Fig. 5).

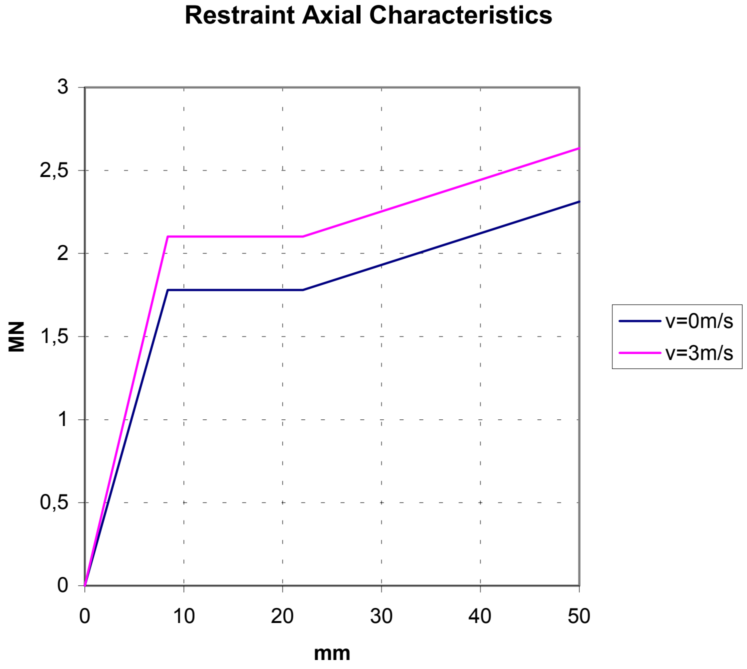

Fig. 6 Restraint axial force

The assumed resultant axial force of the whip restraint related to the relative displacement and relative velocity of the uncoupled pipe cross-sections is presented in Fig. 6. With an initial gap of 1 mm the resultant stiffness of the elements 1602 modelling the restraint axial static characteristic leg is related to the relative displacement as shown in Fig. 7. The shift from static to dynamic characteristics is due to the viscous property of the element 1602.

Fig. 7 Restraint axial stiffness

GERB VISCOUS DAMPER MODEL

Model of a viscous dampers GERB has a form of a twofold Maxwell model (Fig. 8). Its finite element realization consists of special non-linear elements SYSTUS 1602. There are two groups of GERB dampers applied to the SG, each consisting of six dampers. The finite element model of such a group is shown in Fig. 9. In each Maxwell model one element 1602 has a given stiffness and the other a given damping coefficient (Fig. 9).

Based on the report [4] the values of k_i and c_i coefficients are taken as

$k_1 = 21764$ [N/mm], $c_1 = 492$ [Ns/mm], $k_2 = 29747$ [N/mm], $c_2 = 185,1$ [Ns/mm].

These coefficients are chosen to approximate the equivalent frequency dependant equivalent stiffness of the damper $C(f)$ by the equivalent stiffness $C_M(f)$ of the twofold Maxwell model.

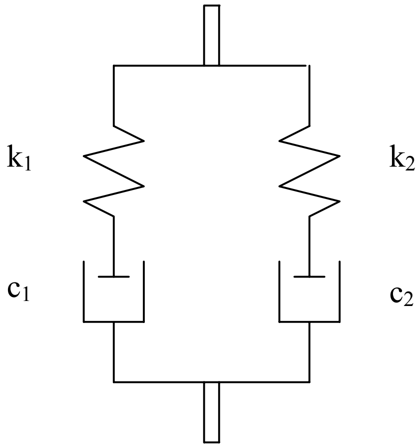

Fig. 8 Maxwell model

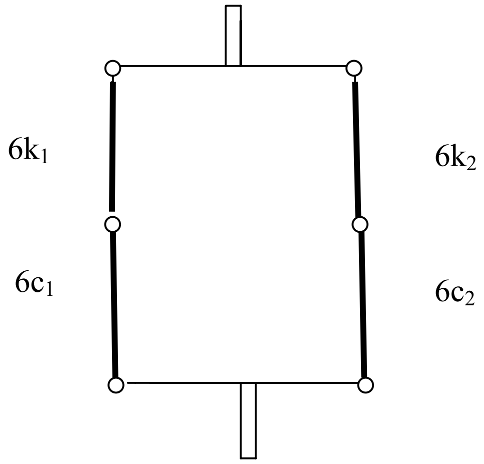

Fig.9 FEM model of 6 GERB dampers

STEAM LINE WHIP - WHIP RESTRAINT ACTION

The action of the whip restraint let be characterized by the axial relative motion of the broken ends of the steam pipe and the steam collector. Analysis of the system transient motion yields relative displacement – time diagram of the node 12726 on the steam pipe and of the node 7325 on the collector and relative velocity – time diagram of these nodes as shown in Figs. 10 and 11 respectively.

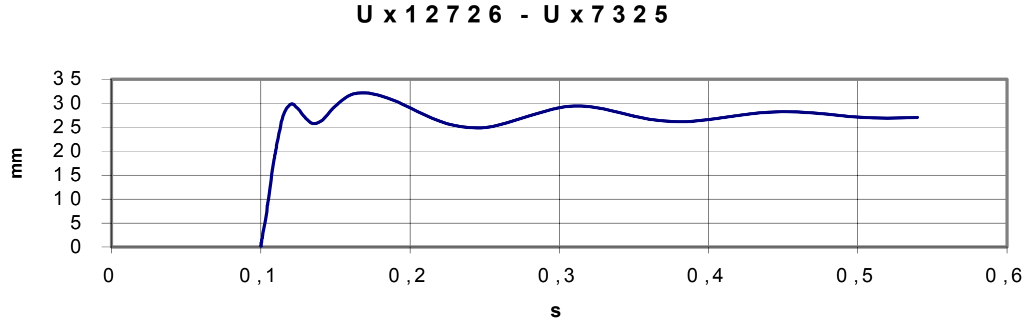

Fig. 10 relative displacement

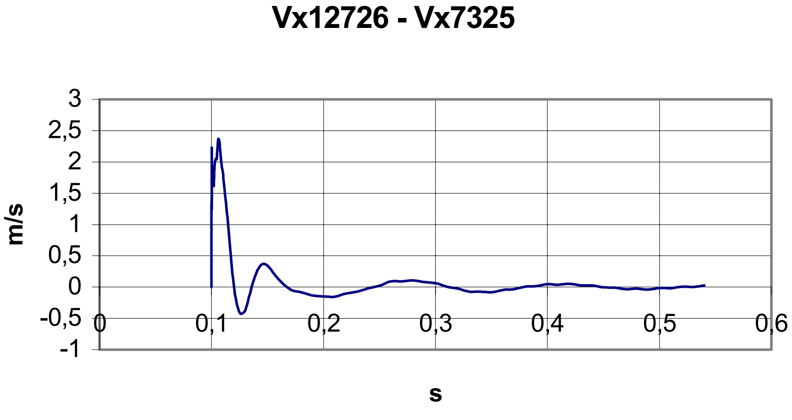

Fig. 11 relative velocity

The relative displacement of the node No. 12726 of the steam pipe relative to the node No. 73525 attains about 33 mm The respective relative velocity does not exceed 2,5 m/s.

The displacement of the steam collector relative to the steam generator body related to time is shown by a diagram in Fig. 12. In case of a pipeline without the whip restraint the maximum displacement of the steam collector relative to the steam generator body would be 79,3 mm.

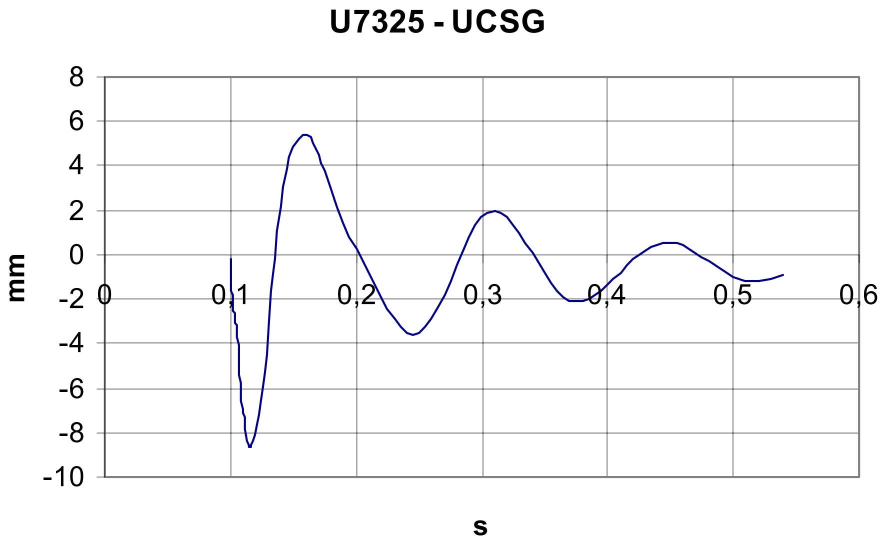

Fig. 12 Displacement of the steam collector to SG

STEAM LINE WHIP – SG MOTION AND GERB DAMPERS REACTIONS

The dynamic components of the stream generator (SG) centre of gravity (C.G.) displacement are very small (Fig. 13). The velocity components of the C.G. attain about 5 mm/s (Fig. 14). In case of the whip restraint absence the u_x dynamic displacement component would be about –35 mm, u_y about –15 mm and the velocity components v_x and v_y would attain 120 mm/s and 70 mm/s respectively.

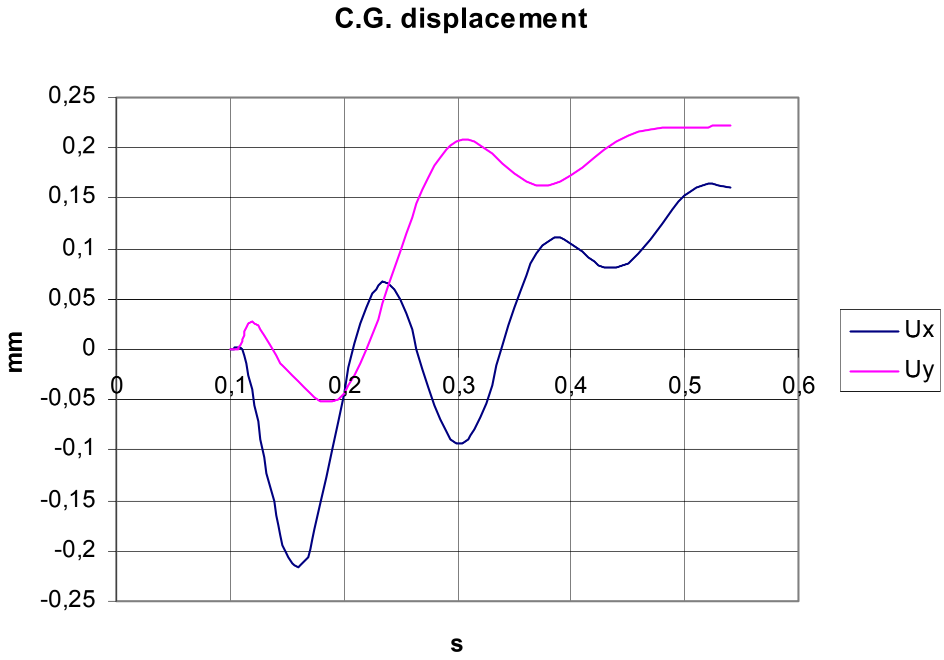

Fig. 13 SG displacement

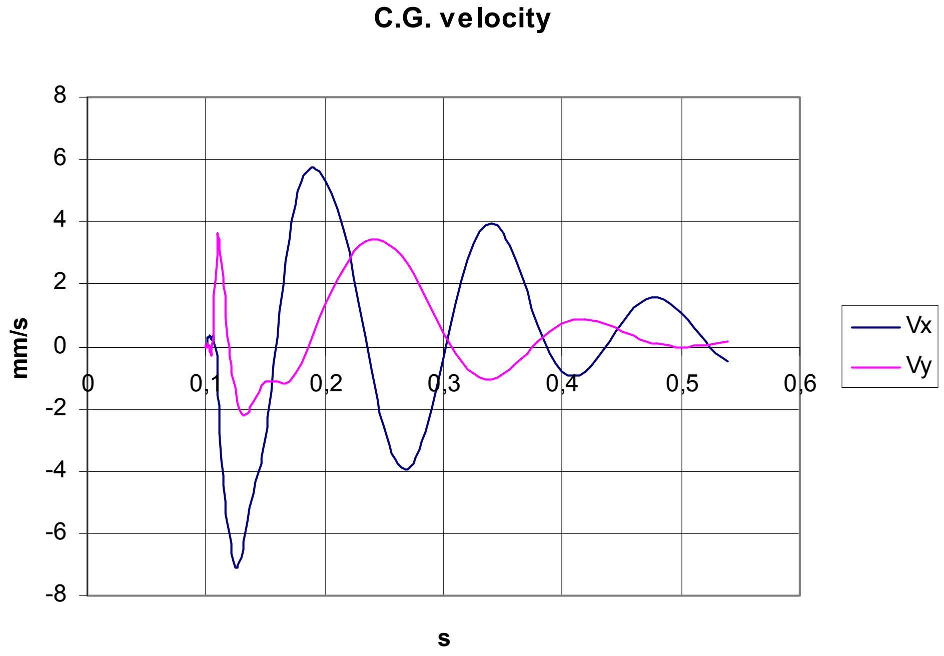

Fig. 14 SG velocity

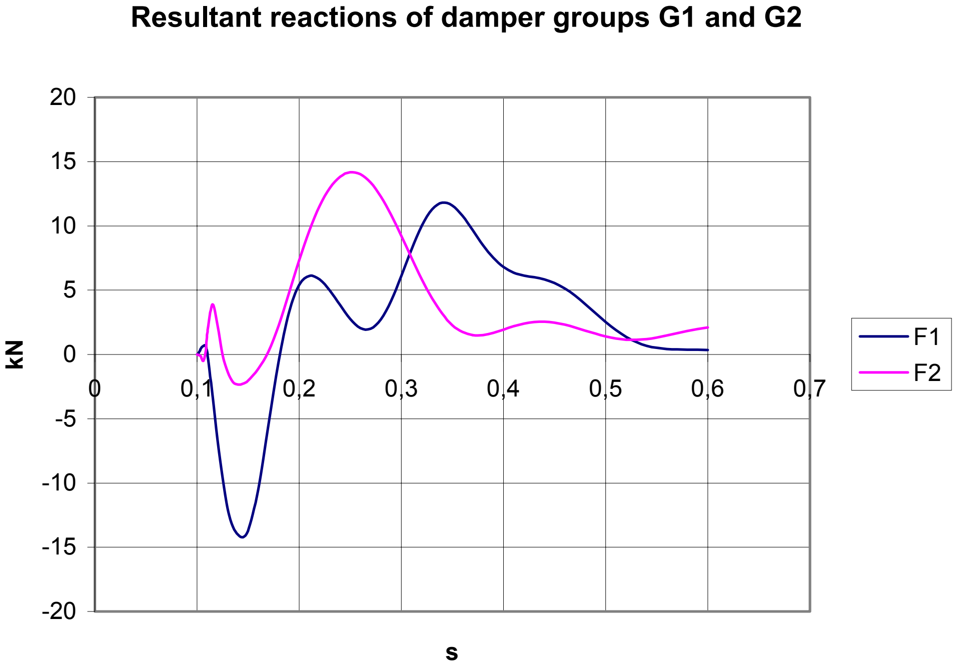

Fig. 15 Dampers reaction

In case of a pipeline without the whip restraint the maximum value of a reaction would be 583 kN still smaller than the admissible load of 600 kN.

STEAM LINE WHIP – INTERNAL FORCES IN THE HOT COOLANT LOOP LEG

Time relations of the dynamic components of the normal force, shear forces, bending moments and twisting moment at the cross-section, where the collector is build-in in the reactor wall related to time are shown in the diagrams of Fig. 16.

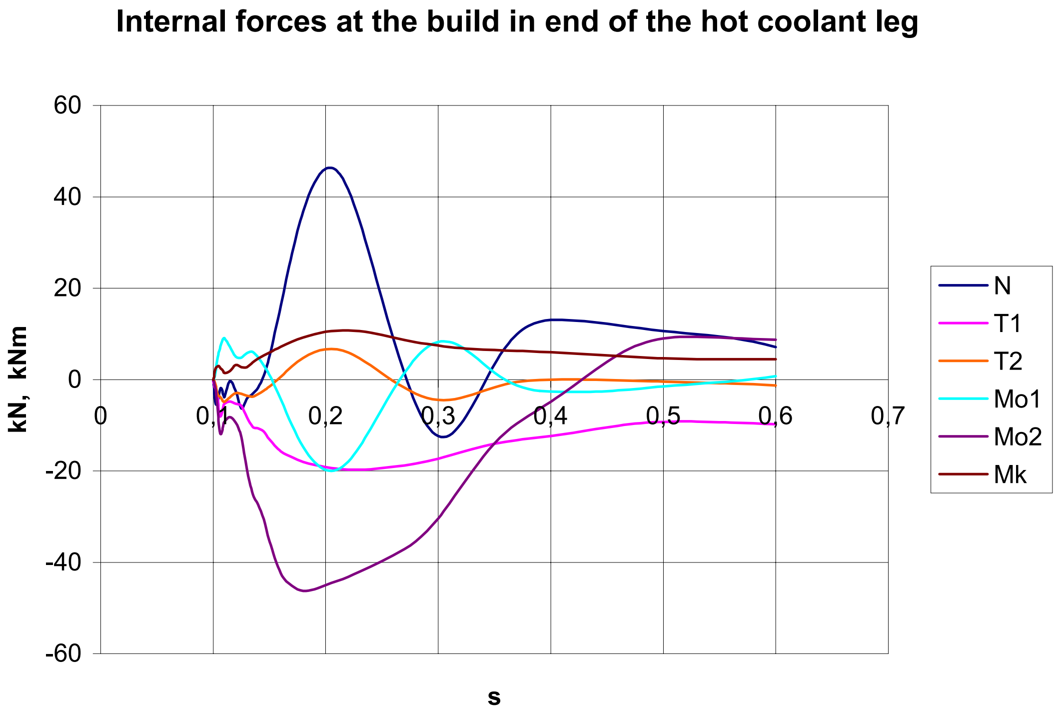

Fig. 16 Internal forces in the hot coolant leg

Without the whip restraint the dynamic internal forces would be about 30 times greater.

CONCLUSIONS

Programme SYSTUS enables to model efficiently a circumferential crack evolution and the whip restraint function. The non-linear whip analysis describes the whip energy by the restraint absorbing element model and proves the restraint property to keep the motion of the released pipeline ends within given limits. It has been found by the whole steam generator system analysis including the GERB dampers that a steam line break at the postulated weld crack with the steam generator collector with a great security safeguards the integrity of this system. Even in a case of whip restraint complete failure the strength of the structure will appear as satisfactory.

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