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ANALYSIS OF THE EARTHQUAKE EFFECT ON A PIPELINE BROKEN BY A CIRCUMFERENTIAL CRACK

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Summary: *Dynamic effects of seismic excitation and of the steam line break in the weld of the steam pipe and the steam collector during an earthquake are analyzed. Generated synthetic acceleration-time histories based on given floor response spectra are used to excite the system. To model the process of a circumferential crack evolution leading to the pressurized pipe rupture and of the whip restraint function a special element in the programme SYSTUS is used. Whip of of the steam line is analyzed and its effect on the steam generator considered.*

Keywords: Steam line break, Seismic excitation; Circumferential crack modelling, Whip of a pipeline, Whip restraint.

1. INTRODUCTION

The dynamic effects of high energy pipe breaks, such as pipe whips and jet forces due to a sudden release of liquids and steam, could lead to a failure of a safety related equipment [1]. With a greatest probability a pipe break in a postulated cross-section may appear during a seismic event effecting at the same time the seismic resistance of the system.

To show the procedure of modelling and analysis of the interaction of a seismic excitation and of a high energy steam pipeline rupture the following problem solution is selected. The break in the weld of the steam pipe and the steam generator collector is postulated to occur at an instant when the vibration of the system due a seismic excitation attains a considerable level. The rupture is assumed to be initiated by a random increase of the pipe internal pressure.

Here 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.

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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 (Fig.1). The whip of the pipeline is described by the response to a sudden uncoupling of the assumed parts of the model and to the seismic excitation by given acceleration-time histories.

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 non-linearities are modelled by SYSTUS elements 1602.

2. SHELL MODEL OF THE SYSTEM

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

Steam generator
Steam collecting legs, collector, steam line till penetration
Reactor coolant pump (simplified)
Primary pipeline hot leg
Primary pipeline cold leg

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

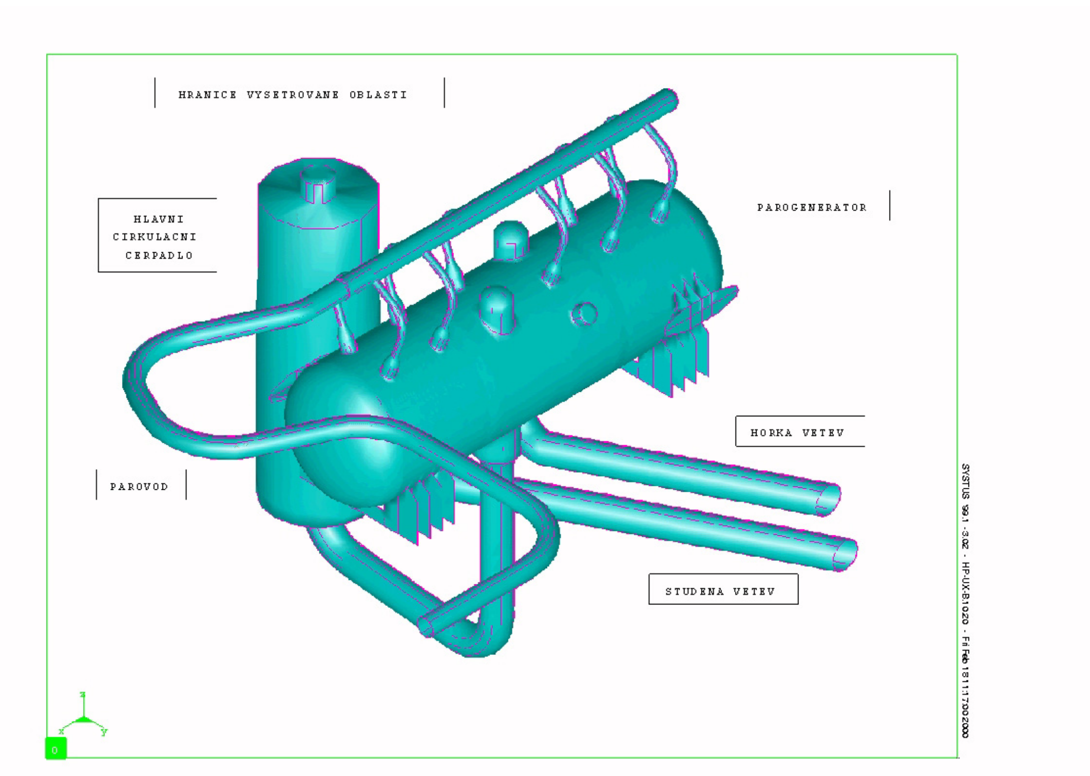

Fig. 1: Model of the system

3. 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 [3].

The stiffness-elongation relation of an average element corresponding to the situation at a time of 3 s is shown in Fig. 2. Till the relative nodal displacement of 0,107mm there is $k_x = 15{,}65\ GNm^{-1}$.

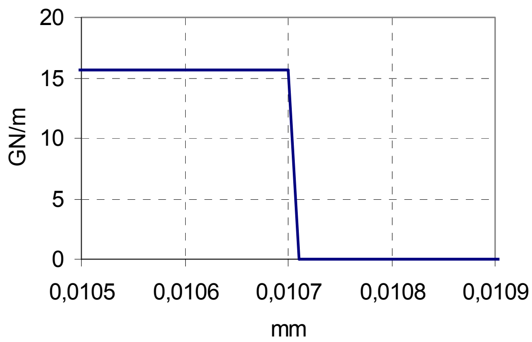

Fig. 2: Break element 1602 stiffness

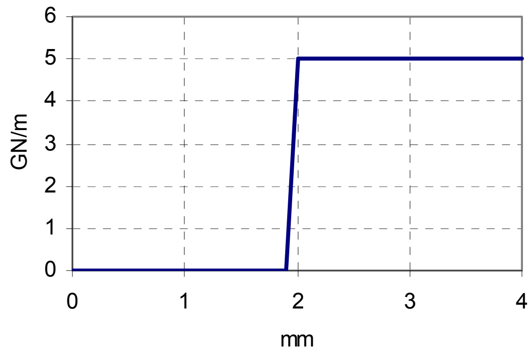

Fig. 3: Lateral element 1602 stiffness

The whip restraint with viscous elements [3] 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. 3). The lateral stiffness coefficients have a similar characteristics. Their magnitudes are $k_y = k_z = 5$ GN/m.

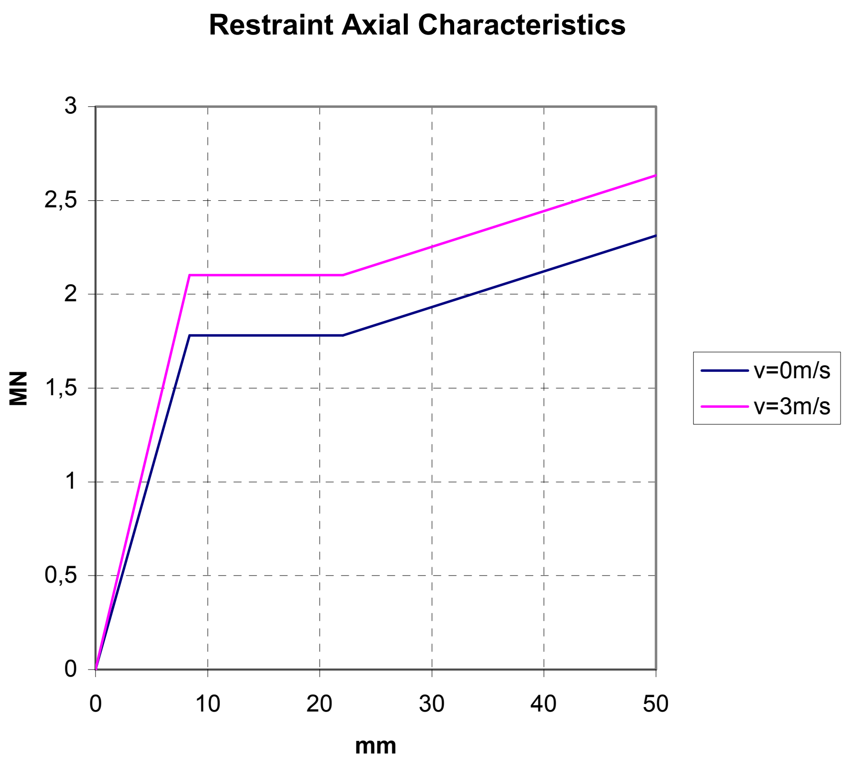

Fig. 4: Restraint axial force

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. 4. With an initial gap of 1 mm the resultant stiffness of the elements 1602 modelling the restraint axial static characteristic leg is related to relative displacement as shown in Fig. 5. The shift from static to dynamic characteristics is due to the viscous property of the element 1602.

Fig. 5: Restraint axial stiffness

4. Seismic Excitation

Seismic excitation is given by floor response spectra depicted by a red line in Figures 6 and 7. To be able to solve the response of a non-linear system synthetic acceleration-time histories based on the given response spectra has been generated.

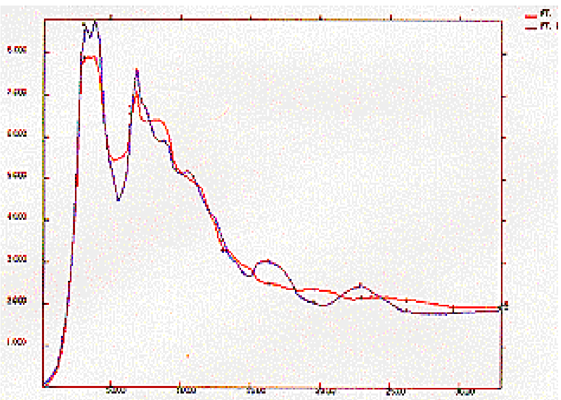

Fig. 6: Horizontal response spectra

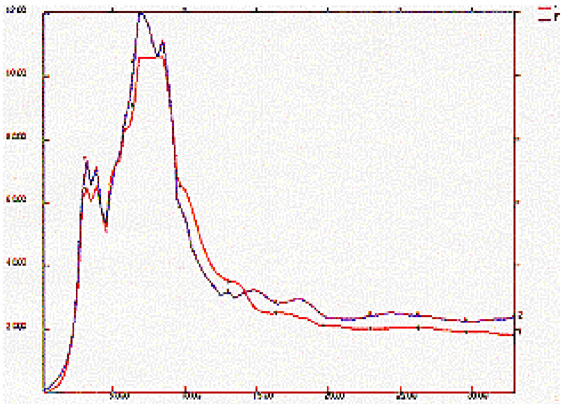

Fig. 7: Vertical response spectra

To do so a program ACCLGS was developed based on the following algorithm. An acceleration time history let be equal to harmonic series

$$a(t) = \sum_{j=1}^{n} a_j (-1)^j \Omega_j^2 \sin \Omega_j t , \qquad (1)$$

The frequencies Ω_j equal to those in the response spectra tables. The response of an oscillator of natural frequency ω_i and a damping ratio ζ to this ground acceleration is

$$x_i = \sum_{j=1}^{n} X_{ij} (-1)^j \sin(\Omega_j t + \varepsilon_{ij}), \qquad (2)$$

where

$$X_{ij} = a_j \frac{z_{ij}^2}{\sqrt{(1-z_{ij}^2)^2 + (2\zeta z_{ij})^2}} \ , \ z_{ij} = \frac{\Omega_j}{\omega_i},$$

$$\sin\varepsilon_{ij} = -\frac{2\xi z_{ij}}{\sqrt{(1-z_{ij}^2)^2 + (2\zeta z_{ij})^2}}, \ \cos\varepsilon_{ij} = \frac{1-z_{ij}^2}{\sqrt{(1-z_{ij}^2)^2 + (2\zeta z_{ij})^2}} \ . \qquad (3)$$

A component $X_{ij}\sin(\omega_i t + \varepsilon_{ij})$, $\left(\Omega_j = \omega_i, \varepsilon_{ij} = -\frac{\pi}{2}\right)$ has its maximum magnitude at

$$t_i = \frac{m\pi}{\omega_i} \ , \quad m = 1,2,3.... \qquad (4)$$

From Eqs (1) to (4) it follows that at a time t_i the sum of component absolute values is

$$x_i(t_i)_{abs} = \sum_{l=1}^{n} a_j z_{ij}^2 \frac{(1-z_{ij}^2)\sin m\pi z_{ij} - 2\zeta z_{ij}\cos m\pi z_{ij}}{(1-z_{ij}^2)^2 - (2\zeta z_{ij})^2} = \sum_{j=1}^{n} a_j A_{ij} \ . \qquad (5)$$

Here is i = 1,2,...n. When substituting

$$x_i(t_i)_{abs} = \frac{S_{ai}}{\omega_i^2}, \qquad (6)$$

where S_{ai} is the spectrum value corresponding to a frequency f_i, we get a system of algebraic equations to calculate the unknowns a_j

$$\mathbf{A}\,\mathbf{a} = \mathbf{s}\ . \qquad (7)$$

Arranging a_j to obtain response spectra drawn by a dark line in Figures 6 and 7 enveloping the given response spectra we get the synthetic acceleration time histories (Fig. 8 and 9).

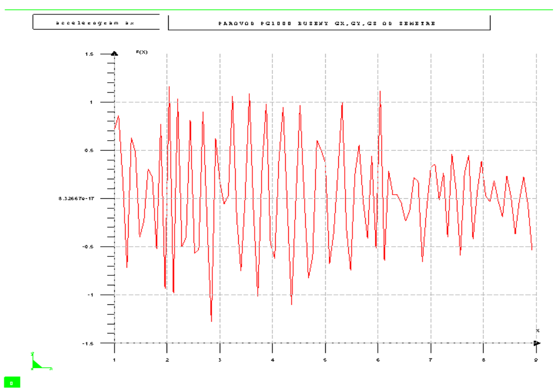

Fig. 8: Horizontal accelerogram

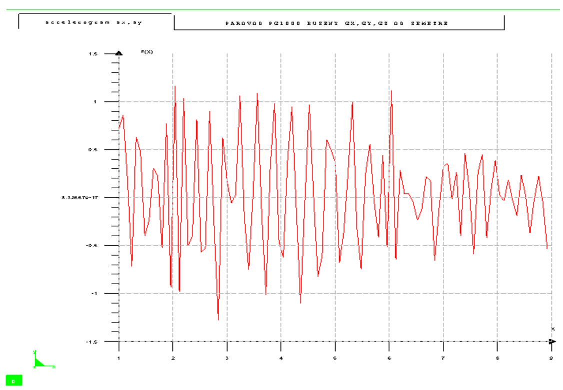

Fig. 9: Vertical accelerogram

5. Response of the System

The response to the seismic excitation let be characterized by the displacements and velocities of the nodes joined by SYSTUS elements 1602. In the coupled state the displacements of an upper node are shown in Fig. 10 and the respective velocities in Fig. 11 (u_x and v_x by a red line, u_y and v_y by a green line, u_z and v_z by a blue line).

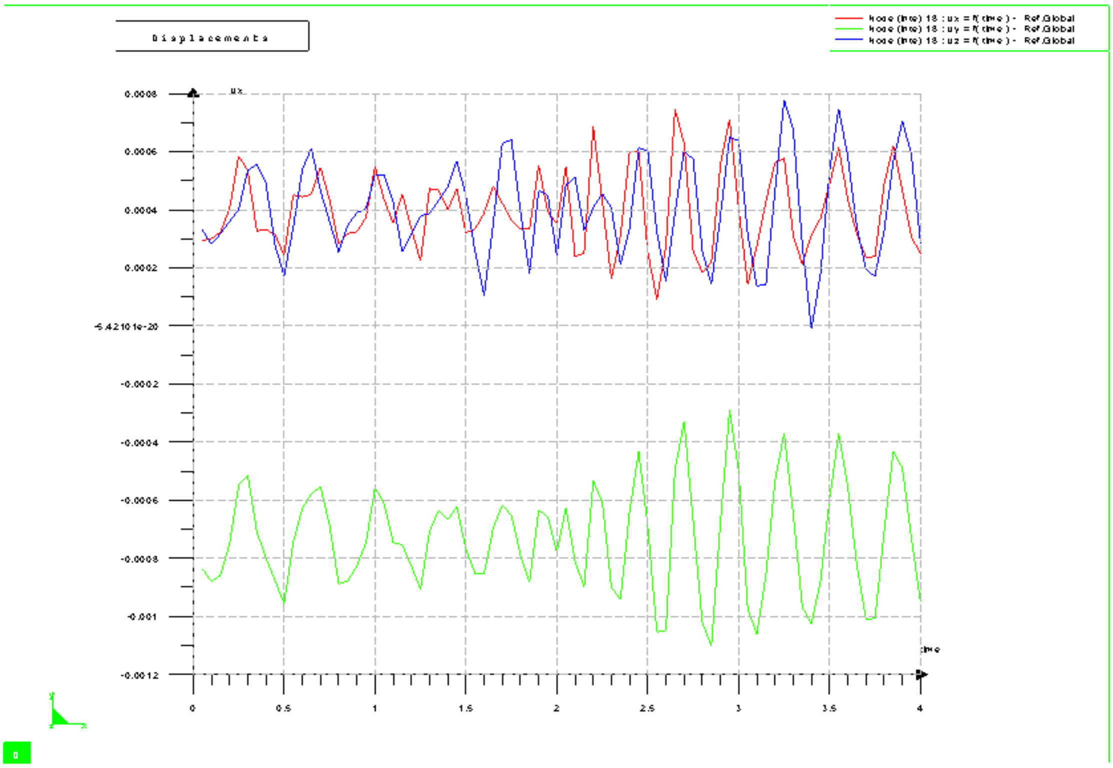

Fig. 10: Displacement

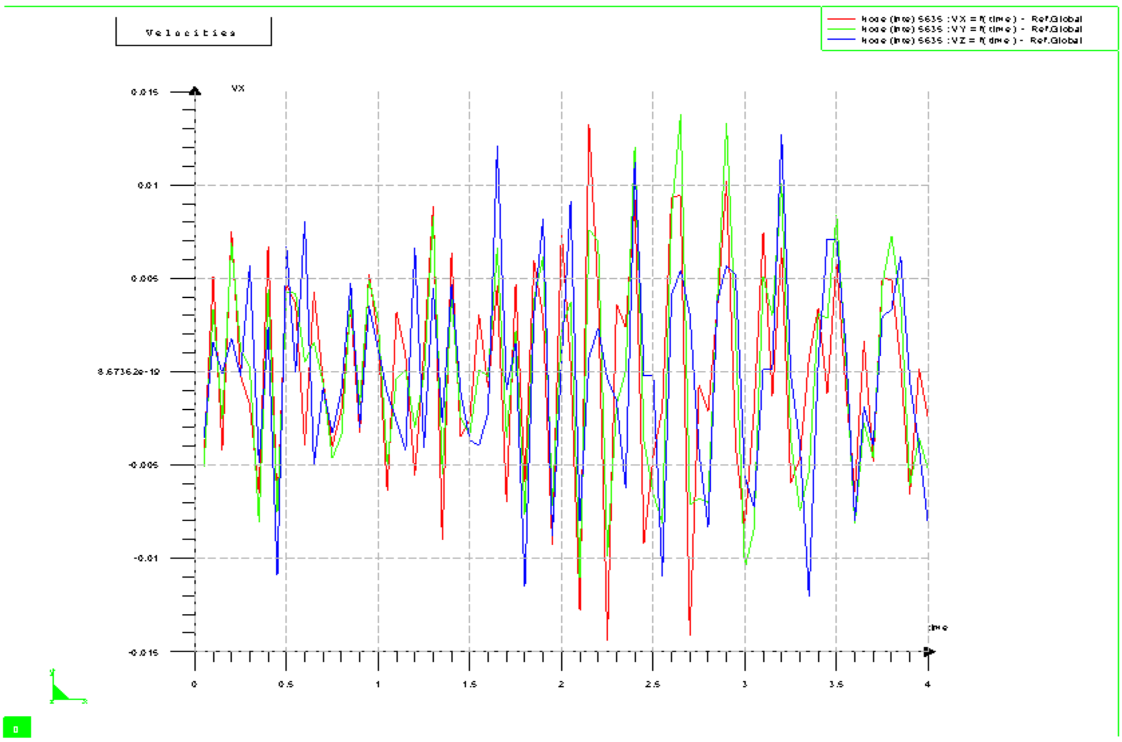

Fig. 11: Velocity

In the uncoupled model simulating a broken pipeline the longitudinal displacements u_x are shown in Fig. 12, velocities v_x in Fig.13 and the lateral displacements u_y and u_z in Fig. 14 and 15 (a node on the steam line - red line, a corresponding node on the collector - blue line).

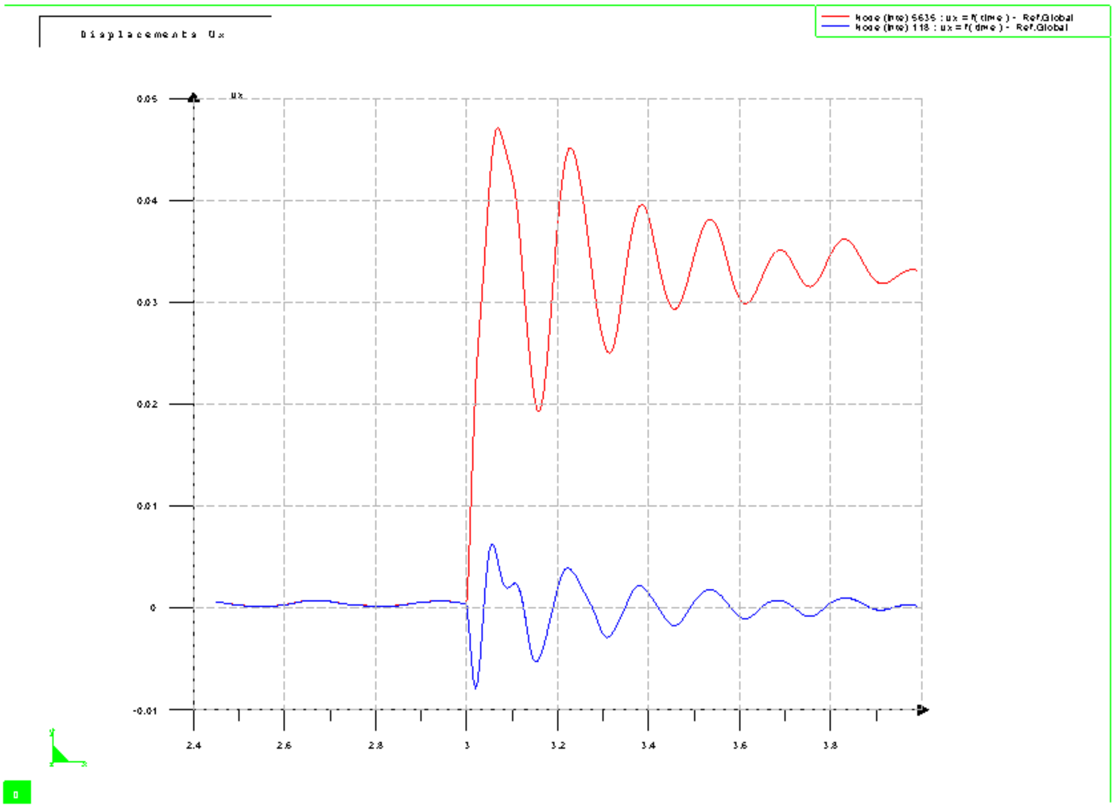

Fig. 12: Displacement u_x

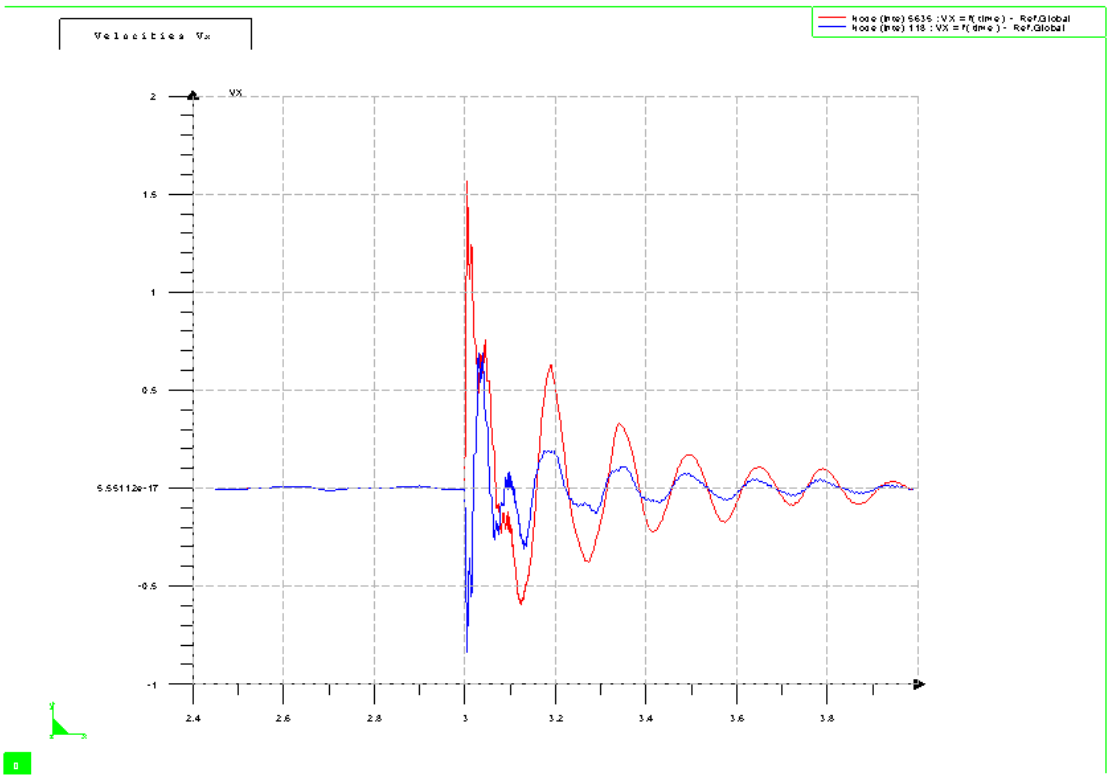

Fig. 13: Velocity v_x

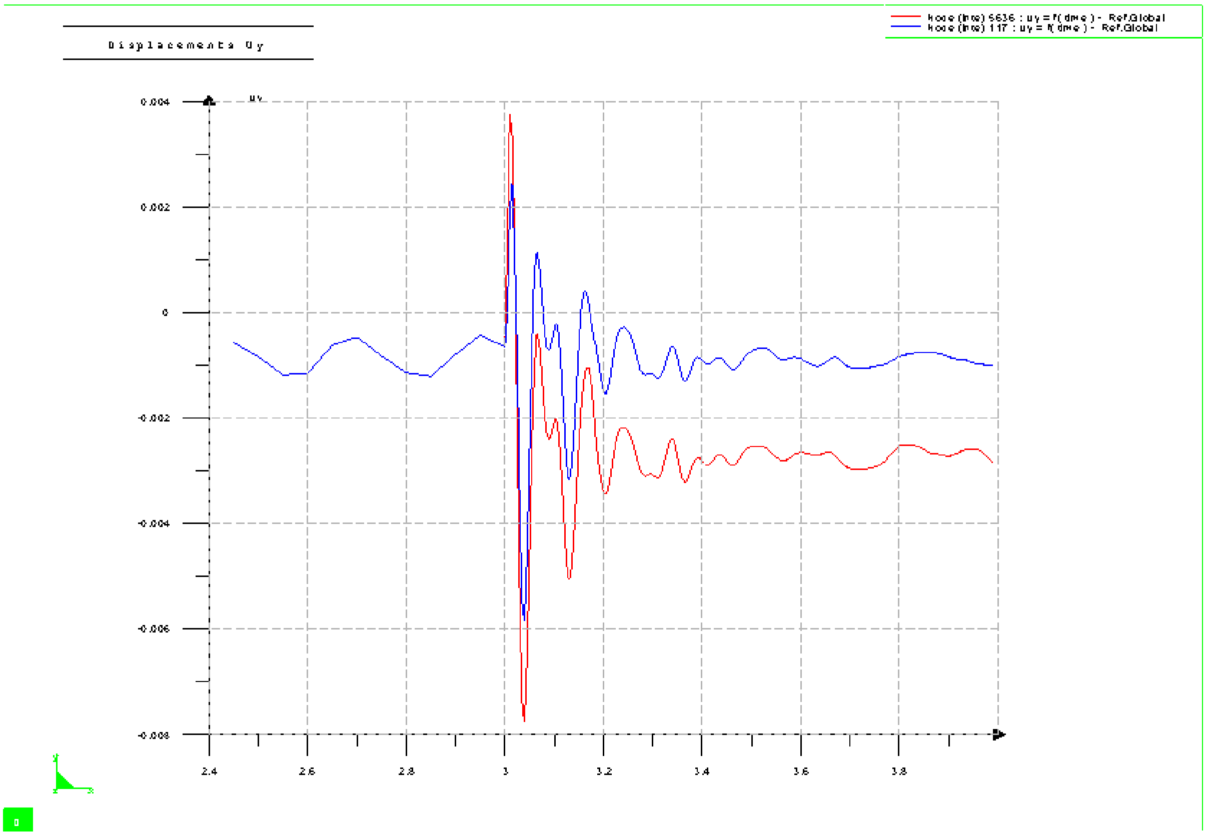

Fig. 14: Displacement u_y

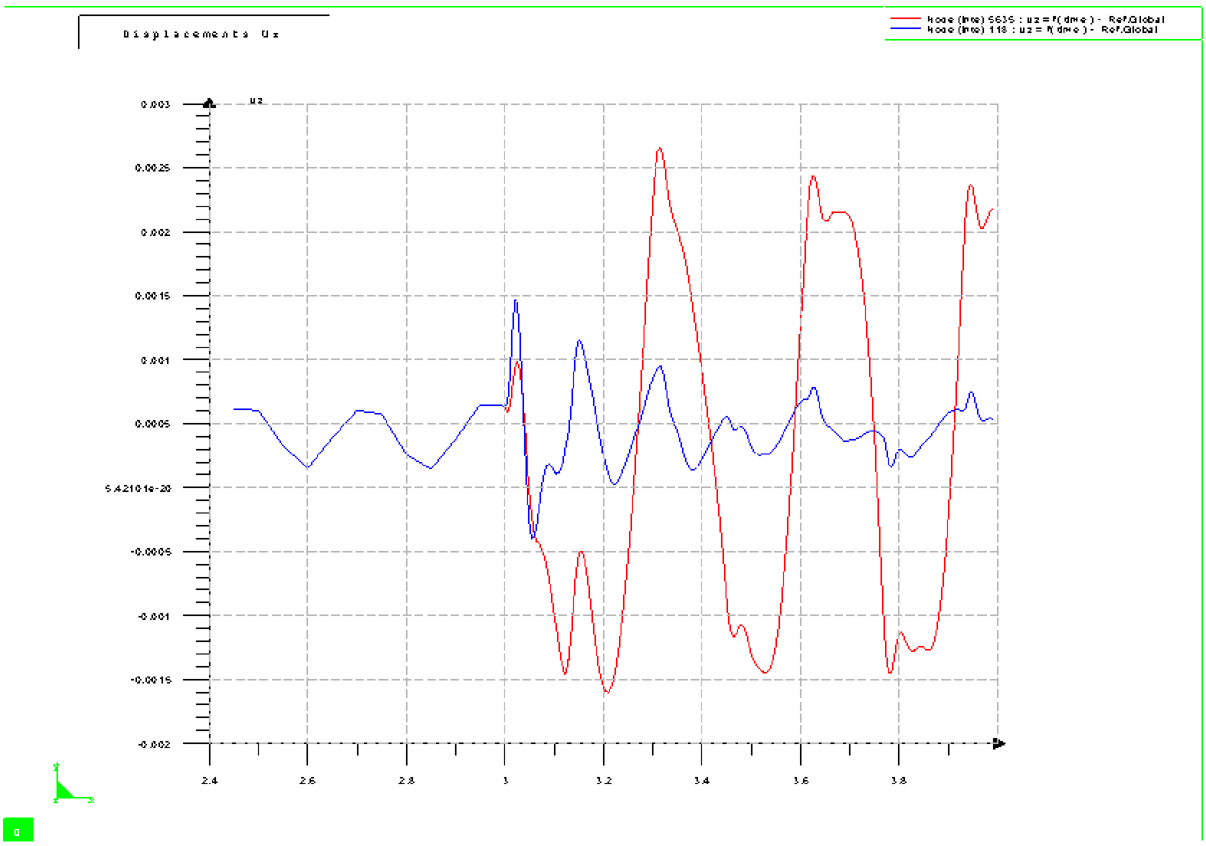

Fig. 15: Displacement u_z

The relative displacement and velocity-time relations of a steam line upper node and of its corresponding collector node are shown in Figures 16 and 17.

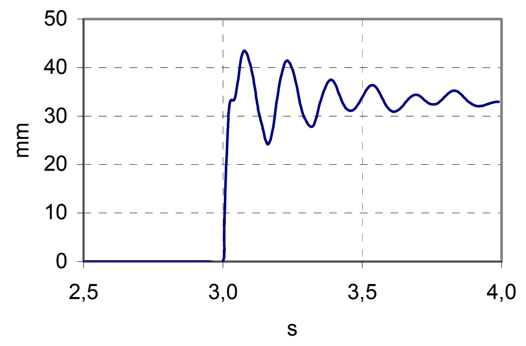

Figure 16: Relative displacement u_x

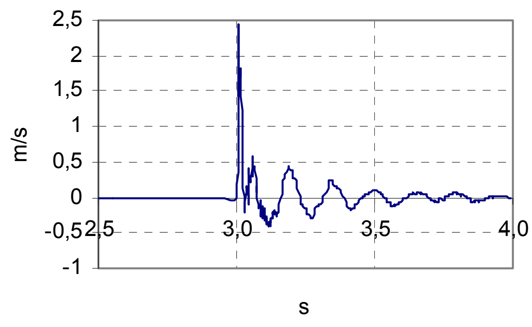

Figure 17: Relative velocity v_x

The forces in the restraint elements 1602 related to time are presented in Fig. 18. The effect of the seismic excitation can be seen in the period prior to the pipe rupture simulation at the instant t = 3 s. These forces correspond to pipe internal forces. Following the pipe rupture, which take place at a time of 3 s,. these forces correspond to the actual forces in the restraint structural elements.

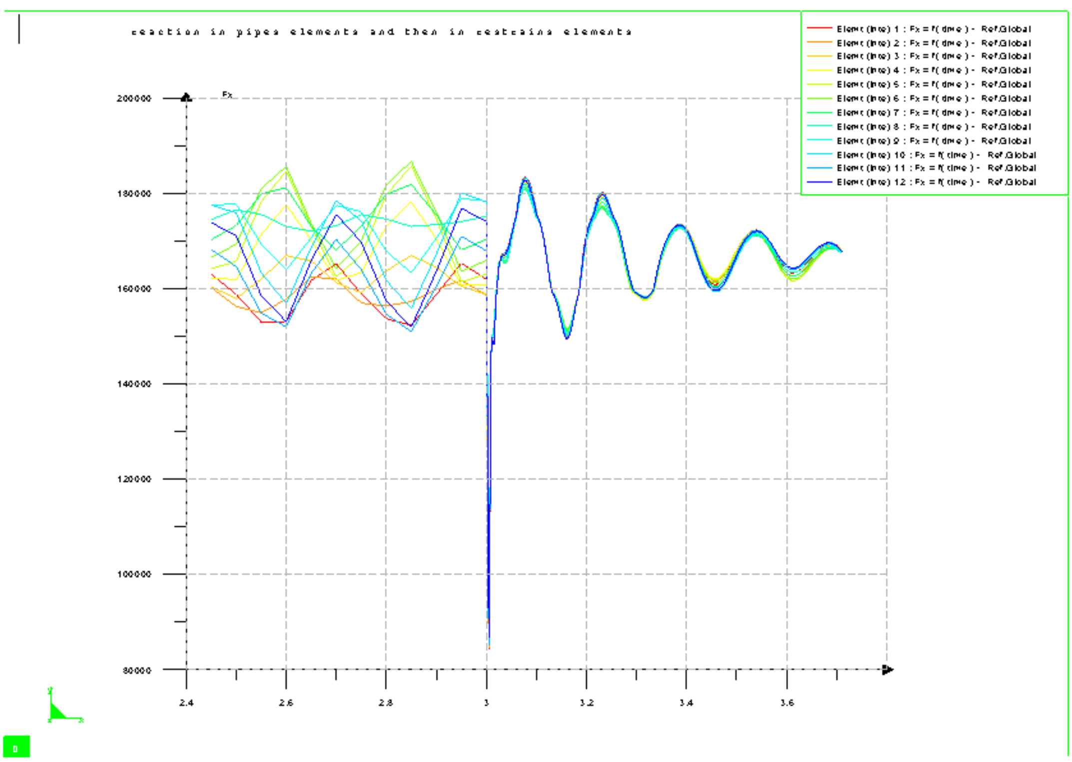

Fig. 18: Axial force in the restraint elements

The displacements of the steam line and of the steam collector distribution at an instant t = 3,07 s of maximum relative displacement can be seen in Figure 19.

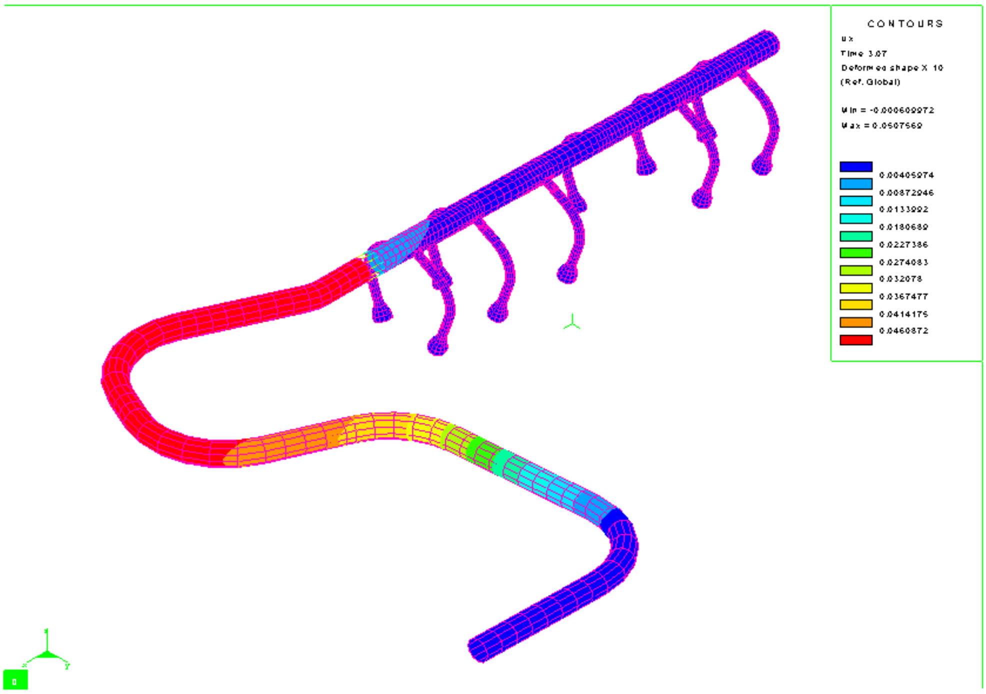

Fig. 19: Displacements along the pipeline

6. Conclusion

It is shown how a seismic excitation can contribute to a possible pipe rupture. Programme SYSTUS enables to model efficiently a circumferential crack evolution and the whip restraint function. The non-linear whip analysis describes the whip energy absorbing by the restraint model. This analysis proves the restraint effect to keep the broken pipe ends relative lateral displacements within the limits of ±2 mm. This is achieved by intermittent contacts of pipe ends with a protective restraint tube. The lateral pipeline motion is much more effected by the seismic excitation. than the axial whip motion. The restraint property to keep the motion of the released pipeline ends within given limits safeguards the seismic resistance of the broken pipeline as well.

7. References

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