An Analytical Validation of Simplified Methods for the Assessment of Pipe Whip Characteristics

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ABSTRACT

The consequences of major pipe breaks potentially occurring inside and outside the containment vessel of a nuclear power plant shall be mitigated in accordance with specific regulations ([1], [2]).

Aim of this paper is the validation of simplified methods currently used for the assessment of pipe whip characteristics, as required for an evaluation of potential consequences on safety-related components or equipment. A definition of pipe whip effects is also required for the design of adequate PWRD (Pipe Whip Restraint Devices), whenever these devices prove necessary to reduce such effects to acceptable levels.

This validation is sought through a comparative analysis between issues by simplified approaches, ([3], [4]), based on Static Analysis or Energy Balance Methods, and from detailed Time History elastic-plastic calculations.

The present application is related to main piping systems, MFW (Main Feed-Water) and MS (Main Steam) of the BOP portion of Cernavoda (Romania) NPP Unit 2, a CANDU nuclear power plant presently under construction. Only high-energy systems as defined in [1] are taken into account for postulated Pipe Break Locations (PBL).

The analysis is limited to circumferential breaks potentially occurring at most critical piping locations (terminal ends or high-stress intermediate locations), no longitudinal breaks or leakage through wall cracks being addressed.

The nonlinear time history analysis is performed for some typical piping layouts by means of finite element program ANSYS Version 5.3, [7]. Only "free whip" is investigated, as no Pipe Whip Restraint Devices (PWRD) are considered.

Major issues regard the location of the "plastic hinge" developing on the line under the effect of the jet thrust load at the break and the dynamic response of the ruptured pipe. Other significant outcomes are the time histories of impact mass and velocity at whipping ends, for an estimation of potential effects on safety-related structures.

The comparison between results from Time History and from Static Analysis or Energy Balance methods is performed through some basic assumptions about the plastic hinge location in relation to piping layout near the break.

The simplified approach appears well suited for a conservative estimation of pipe whip characteristics, both as regards maximum displacement ranges of the whipping pipe and maximum impact loads on potential targets.

KEY WORDS: circumferential break, high-energy piping, blowdown, jet thrust, free whip, dynamic, rebound, plastic hinge, run, elbow, layout, support, gap, rupture restraint, displacement, target, impact mass, kinetic energy, velocity, impact load, time history, integration, energy balance, static analysis.

INTRODUCTION

A rupture in high-energy piping (i.e. with maximum operating pressure over 275psig or temperature over 200°F) may lead to severe dynamic effects on systems or components important to safety, that are to be appropriately protected, as required by US Federal Regulations [1]. Piping breaks should be postulated at locations with the greatest potential for failure under loading conditions associated with specific seismic events and operational plant conditions, usually at terminal ends and intermediate high-stress locations accordingly to criteria of [2].

The consequences of a postulated rupture include pipe whip and jet impingement loads, as well as compartment pressurisation, environmental conditions and flooding. The protection against these effects should preferably be achieved through an initial designed-in separation or enclosure to isolate the pipe from safety-related systems or components. Alternatively, essential structures are to be designed to withstand potential loads from a postulated break.

In nuclear power plants, due to complexity of layout and design, this is often impractical and "backfit" solutions to pipe break effects must be adopted, through the provision of additional protection, such as restraints or barriers [3].

This paper is focused on some critical features related to the evaluation of potential effects of a postulated rupture in a high-energy pipe and to PWRD design, with particular regard to the dynamic response following a full separation circumferential (or "guillotine") break in an unrestrained piping portion.

EVALUATION OF PIPING DYNAMIC RESPONSE FOLLOWING A BREAK

Pipe Internal Load Effects

The release of fluid from high-energy piping may result in significant changes of flow characteristics within the pipe, potentially inducing reaction forces able to excite the system and cause an uncontrolled motion (the "pipe whip"). As a result, nearby safety-related structures or components may be overloaded or otherwise damaged.

In a conservative approach, jet thrust loads resulting from a full separation break may be simulated by means of a quasi-steady-state Jet Force ($\mathbf{F_j}$), acting after a Break Opening Time of 1ms, as given by equation:

$$F_j = A_e (C_T P_0 - P_a) \cong C_T P_0 A_e \quad (1)$$

where the thrust coefficient (C_T) is generally assumed in the range between 1.26 (for saturated or superheated steam jets) and 2.0 (for non-flashing water jets due to blowdown of cold water, i.e. at temperatures below 100°C).

Analytical Methods for Pipe Whip Assessment and Restraint Design

The evaluation of piping response following a break should assess the capability of the overall system (piping, restraints and support structures) to dissipate the total energy accumulated during the dynamic event and to withstand the steady state fluid forces (i.e. when motion ceases). Among the acceptable alternatives for the pipe whip evaluation, the following methods are the most commonly retained for pipe break analysis of high-energy systems.

A) Dynamic Time History

A dynamic time history analysis, being often time-consuming, should be a "last resource" method, to be used only if conservatism of simplified models results in too large calculated loads on structures or restraints. The model of piping and pipe whip restraints should adequately reflect its dynamic characteristics, taking into account inertia and stiffness properties of the complete system, as well as the effects of material inelastic behaviour and large deformations. The maximum initial clearance at restraints (the "acceleration gap") should be used in calculations, to account for the most adverse dynamic effects of pipe whip. The pipe history forcing function shall be applied at each pipe break end, and the time history response, in terms of restraint loads, pipe deformations, etc., computed by numerical integration [1].

In a simplified approach, a limited portion of the piping system may be modelled in the analysis instead of the complete system; proper consideration should be given in this case to dynamic coupling between the portion to be analysed and the remainder of the system. Conservative assumptions may also regard the time history forcing functions and the representation of the dynamic characteristics of the pipe whip restraint system.

B) Energy Balance Analysis

This method is based upon the main hypothesis that the kinetic energy generated during the first quarter cycle movement of the ruptured pipe (initial and final pipe velocities equal to zero) and imparted to the piping and restraint system through impact is converted into equivalent strain energy. The energy absorbed by the pipe deformation may be deducted from the total energy imparted to the system. As with a dynamic analysis, the input energy should be conservatively evaluated taking into account the maximum possible initial gap at restraints.

Since energy balance cannot account for any time dependence, a constant jet thrust force shall be conservatively assumed, as given by Equation (1). For applications where pipe rebound may occur, an amplification factor of **1.1** is recommended to account for the potential occurrence of the maximum stress or strain in the pipe whip restraint after the first quarter cycle of response [2]. A simple collapse mechanism is generally assumed to predict the pipe behaviour and conservative laws to assess the span distance between break and primary plastic hinge, as well as the maximum impact load on any nearby structure [4]. The length to the main plastic hinge is evaluated taking into account the influence of restraint location (if any) and of the energy absorbed by pipe bending, as well as of the mass of the attached pipe [3].

The energy balance method is well suited for the design of energy absorbing restraints, which is based on the evaluation of pipe and target post-impact deformation through the extrapolation of experimental pipe crush data [5].

C) Static Analysis Approach

In this approach, a conservative amplification factor (the Dynamic Load Factor) is used in the restraint design to establish the magnitude of the forcing function induced by the jet thrust force following the postulated pipe break, and the ruptured system is analysed statically. A conservative value should be used for this amplification factor, as drawn from detailed dynamic analyses of comparable systems; a commonly accepted DLF for a preliminary design is **2**.

METHODOLOGICAL APPROACH FOR CERNAVODA 2 PIPE BREAK ANALYSIS

Reference Method

Cernavoda 2 NPP pipe break analysis was related to guillotine breaks in MFW and MS systems, as postulated on the base of maximum stresses issued from mechanical analysis. Among all potential PBL, the "aggressive" points, i.e. those breaks that can result in a damage of essential structure or component, were identified through simplified assumptions about the whip maximum potential reach, considering any safety-related item near the postulated rupture.

Pipe rupture restraints (PWRD) are required at all aggressive PBL, where no other reasonable engineering solution, such as a change in plant layout, can be adopted to mitigate the potential pipe whip effects. The PWRD design verification is based on the Static Analysis Approach, as far as the design of elastic PWRD is concerned, or on the Energy Balance Method, whenever the use of energy absorbing restraints proves necessary. Such devices are often required to restrain large size pipes containing sub-cooled water (or non-flashing liquid), due to the large jet thrust loads experienced by these pipes after a guillotine break (as it happens for the MFW system).

At this stage of the project, even for aggressive PBL requiring a restraint device, the use of a dynamic time history analysis of the complete system piping-restraints was not deemed as necessary. Instead, a simplified dynamic analysis of piping systems with similar layouts and loading conditions was performed as a validation of the simplified methods to be adopted for the assessment of the free whip response in the phase of aggressive PBL identification.

Free Whip Investigation

A simplified free whip analysis was carried out for each of the high-energy piping locations identified on MFW and MS systems as potential breaks on the base of stress analysis results.

The assumptions adopted in this analysis were related to the following main pipe whip characteristics [3], [4]:

a) piping length to main plastic hinge, i.e. distance between broken run axis and hinge location;
b) effective impact mass;
c) kinetic energy and velocity of the whipping pipe ends.

A plastic hinge may be formed in the bending plane, but complicated piping layouts may lead to the creation of a torsion hinge, with a whip motion outside the main bending plane. Conservative assumptions were then to be made to estimate maximum potential displacements around the hinge. The length to main plastic hinge ($\mathbf{L_h}$) was estimated by means of two different formulations. The first approach assumes the typical collapse mechanism of a cantilever pipe with end load (Figure 1), with $\mathbf{L_h}$ given by equation [4]:

$$L_h = M_p / F_b \tag{2}$$

For small deformations, the pipe plastic bending moment ($\mathbf{M_p}$) may be given by the section elastic modulus ($\mathbf{M_{Lim}}$):

$M_p = M_{Lim} = S_y Z_p$

For large deformations, when strain hardening occurs, a better approximation is given by $\mathbf{M'_p}$ from the relationship:

$M'_p = S_y Z_p + (S_u - S_y) Z_e$

The above formulation, which is commonly used in static analysis, neglects any influence of the pipe length from the break to the first elbow, as well as any restraint effect. It allows a conservative estimation of the minimum unrestrained length of pipe inducing the formation of a plastic hinge, but it may lead to unrealistically short hinge lengths. On the other hand, for the assessment of the aggressive PBL, the envelope of the whipping pipe should assume a pivotal motion around a plastic hinge located at the maximum distance from the break point. For this reason, the following, more realistic, formulation for $\mathbf{L_h}$ is often used in restraint design based on energy balance analysis [3]:

$$L_h = \frac{3M_p}{2F_b}\left(1+\sqrt{1+\frac{8}{3}\frac{LF_b}{M_p}}\right) \tag{3}$$

The above equation takes into account the inertial effect of the length from pipe break to first elbow ($\mathbf{L}$). In addition, the presence of restraints could be considered through an iterative evaluation of the plastic bending moment $\mathbf{M_p}$ with the method of Gerber [6], taking into account the strain hardening properties of the material and the real rotation of the pipe at the hinge location (see Figure 2). For a free whip analysis considering large deformations, the plastic bending moment may be assumed as equal to the resisting ultimate moment M'_p previously defined.

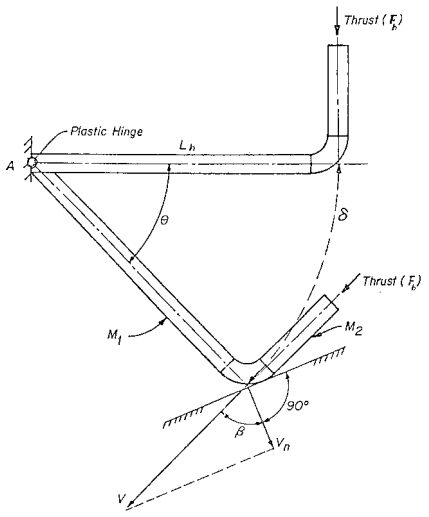

Figure 1 – Cantilever Pipe Whip Mechanism

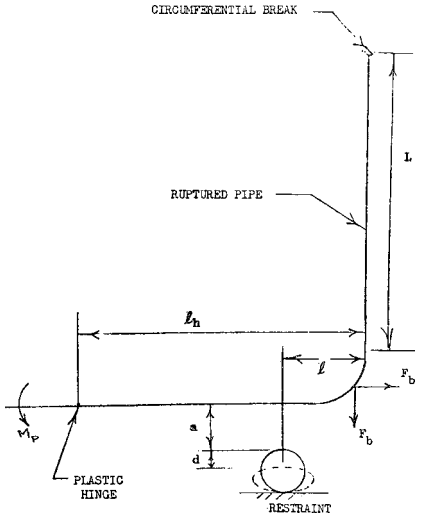

Figure 2 – Restrained Pipe Whip Characteristics

The effective impact mass at the whipping pipe end is usually assumed as one-third of the mass between the first elbow after the break and the main plastic hinge plus the full mass of the first pipe run, in accordance with the simplified pipe whip mechanism of Figure 1, namely:

$$M_i = M_1 / 3 + M_2 \tag{4}$$

The kinetic energy of the impacting pipe after the postulated break may be estimated by the Energy Balance Method, assuming a pipe whip pivotal motion around the plastic hinge, as shown in Figure 1.

The kinetic energy ($\mathbf{E_{kin}}$), which results from the jet thrust work, may be evaluated by equation:

$$E_{kin} = F_b \cdot \delta - M_p \cdot \theta = (F_b \cdot L_h - M_p) \cdot \theta \quad (5)$$

The impact velocity ($\mathbf{V}$) of the whipping pipe may then be estimated by means of equation:

$$E_{kin} = \tfrac{1}{2} I_{AR} \omega^2 = \tfrac{1}{2} I_{AR} (V/L_h)^2 \quad (6)$$

Finally, an estimation of the maximum impact force ($\mathbf{F_{max}}$) on a potential target can be given by equation:

$$F_{max} = V \cdot \sqrt{M_i K} \quad (7)$$

The validity of Equations (2) through (7) is checked in this paper through a simplified dynamic time history analysis of limited portions of piping with similar characteristics and loading conditions.

FREE WHIP TIME HISTORY ANALYSIS

Computer Platform

Free whip calculations were performed on piping finite element models by means of the computer program ANSYS Version 5.3 [7]. These models take into account:

a) the non-linear material properties of the piping, by means of ANSYS elements PIPE20 (plastic straight pipe) and PIPE60 (plastic curved pipe), assuming a classical bilinear kinematic hardening behaviour;
b) the large deflection effects;

Time history analyses were based upon the following main calculation parameters:

a) a variable integration time step, starting from a first step related to system highest frequency of interest;
b) a structural damping coefficient based on a 2% damping ratio at the system main frequency.

Selected Cases for Free Whip Calculations

Four main cases were investigated for the analysis of free whip following pipe ruptures in MFW system, as postulated from stress analysis results:

a) the first case assumes a pipe break at the anchor point PA06 on line G155-12": the model simulates the presence of a rigid clamp at the next anchor point on the same line (PSA96);
b) the second case postulates a rupture at a terminal end of line G003-18" (nozzle connection with Pump P003); this case is analysed by assuming different thrust forces to judge about the most adequate formulation for the main plastic hinge location in relation with the follower jet thrust force assumed at the break end;
c) the third case is derived from the second one, by assuming a change in the piping layout near postulated break (the short piping portion following the first run is not considered in the model);
d) the fourth case is also derived from the second one, with a vertical run, ending at a rigid clamp, beyond the second run. The whole layout, in this case, belongs to a single plane, as often assumed in the vicinity of a postulated break to predict the pipe response in simplified free whip evaluations.

It is observed that most of postulated PBL on MFW and MS lines are associated to piping layout configurations near postulated ruptures which can be essentially reconduced to the layouts assumed in this analysis.

For each model, the coordinate system is the following:

- X = horizontal axis in the transversal direction for Cernavoda 2 NPP Turbine Building (southward)
- Y = vertical axis
- Z = horizontal axis by the right-hand rule.

Main Assumptions

Main assumptions concern the simulation of the jet thrust force and the behaviour of the considered piping supports.

A) Thrust Force

Free whip calculations assume that the jet thrust force on the pipe break end remains directed along the pipe axis during all the pipe whip motion. The thrust force is represented in the model by means of a "following force" acting on the ruptured section always in the normal direction: this is obtained by a pressure load on a fictitious beam element (element BEAM4 of ANSYS) of negligible length, ending at the same section.

The ANSYS model is based upon the conservative assumption of a steady state blowdown force reached within one millisecond, which is the opening time usually considered from crack to full pipe opening. The time history analysis thus assumes a ramp loading from 0 to F_b in 0.001s.

It is pointed out that the prestressed state at time 0, which should account for normal operating conditions before the postulated break, is neglected in this analysis, the associated loads being very low in comparison with the thrust force.

B) Piping Supports

A linear elastic behaviour of piping supports is simulated by linear spring elements (ANSYS element COMBIN14), and the presence of gaps (clearances) between pipe and supports is neglected. A restart analysis would be required for an exact evaluation of pipe motion after the failure of the support function, as supports are generally assumed to fail completely when allowable load rating is exceeded. This simplified assumption still proves adequate for the main scope of this investigation, which essentially covers the location of the primary plastic hinge and the impact mass and velocity at break end. It should however be reminded that, for moderate thrust forces, also supports originally designed for dead weight, thermal, seismic purposes, etc., may significantly affect the pipe whip response.

For rigid and spring supports, calculations assume the stiffness values considered in the piping stress analysis, namely a translational stiffness K_t = 1.7E+08 N/m for rigid supports (value recommended for pipe sizes greater than 8 inches) and K_t = 2.0E+05 N/m for spring supports. These values, assumed as constant all along the free whip motion, allow a conservative estimation of the maximum reactions at supports (beyond the scope of this analysis).

It is also observed that all calculations assume a simplified piping layout ending with a fixed point at the opposite side of the postulated break. This is consistent with the assumption of a pipe whip response not significantly affected by the flexibility of the remainder of the line, provided that at least a run after the plastic hinge location is modelled.

Basic Input Data

Table 1 resumes basic data for the free whip analysis as regards piping characteristics and material properties.

Table 1 – Pipe Size Parameters

SIZE	D_0 (mm)	t_w (mm)	T_D (°C)	P_D (MPa)	P_O (MPa)	TOTAL LINEAR MASS (*) (kg/m)	PIPE MATERIAL	E (T_D) (GPa)	E_p (T_D) (GPa)	S_y (T_D) (MPa)
12” Sch.100	323.9	14.27	187.	5.17	4.92	200.2	SA106 Gr.B	187.1	1.55	209.0
18” Sch.100	457.0	29.36	145.	9.10	7.30	464.2	SA106 Gr.B	189.1	1.56	214.2

(*) including metal, fluid (water) and insulation with jacket

As regards loading conditions, the jet thrust (simulated by means of the follower force at the break end) is evaluated by Equation (1) in cases simulating real conditions, or scaled by adequate factors in test runs. Other considered loads, though of minor influence on pipe whip response, are the dead weight (distributed due to piping or concentrated due to equipment) and internal pressure (the design pressure was conservatively assumed).

TIME HISTORY MAIN OUTCOMES AND COMPARISON WITH SIMPLIFIED APPROACH

Main Results

Main issues of free whip calculations in most significant cases are presented hereafter. They concern time histories of deformed shapes and consequent accumulated plastic strain along the ruptured pipe, as well as impact mass, velocity and kinetic energy at break end. The latter evaluation was limited to cases 1, 3 and 4, for a comparison with corresponding results obtained by means of Equations (4) through (6).

A) Pipe Whip Response and Plastic Hinge Development

Figures 3 through 12 show the piping deformed shapes and corresponding accumulated equivalent plastic strain in some critical elements at different times after the postulated break for the four considered cases; for case 2, Figures 5 through 8 show the different responses corresponding to two different jet thrust forces.

It should be pointed out that time history results can be retained as significant until the ultimate strain of the material (in this case about 0.22) is reached in some element, when plastic instability phenomena overcome.

Table 2 resumes the main results of free whip investigation, in terms of main plastic hinge location.

A comparison is made between time history issues (L^*_h) and simplified evaluations (L_{h2}, L_{h3}), from Equations (2) or (3), the index (’) meaning that M'_p instead of M_{Lim} is used for M_p in Equations (2) and (3).

It is also to be observed that L_h values from the Energy Balance Method in both Tables 2 and 3 have been found taking into account a rebound effect through an amplification factor 1.1 on the blowdown thrust force.

The main hinge lengths thus evaluated may be compared with the lengths to the beginning of the second run (L_{2r}).

For time history, the time of plastic hinge rise (t_{PH}) is also reported, meaning the earliest time at which a significant plastic strain is observed, even if the corresponding location may be not the same where ultimate strain is first reached.

Table 3 gives a comparison between the time history analysis and the simplified energy balance method of Equations (4) through (6), as regards impact mass, kinetic energy and velocity at the impacting end (first elbow) for cases 1, 3 and 4. Time history results are given at the earliest time associated to significant displacements at the first elbow in the jet initial direction (δ_{1e}), when a consolidate plastic hinge may be considered as already acting at some location. The comparison is based upon the whipping pipe rotation θ at time t, as evaluated by time history through the relationship $\delta_{1e} = L_{1e} \sin\theta$ (see Figure 1), L_{1e} being the distance from the first elbow end to the plastic hinge.

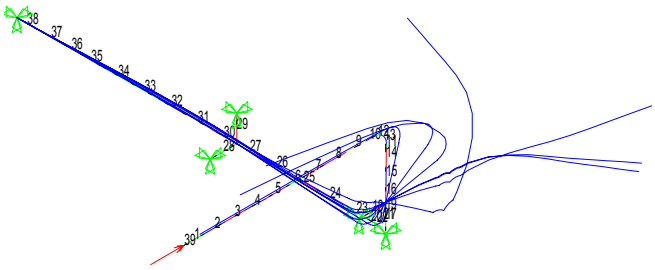

Figure 3 – Case 1 – Free Whip within 311 ms

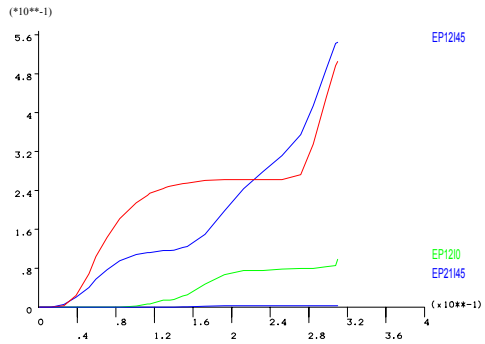

Figure 4 – Case 1 – Plastic Strain in Elements 12, 21

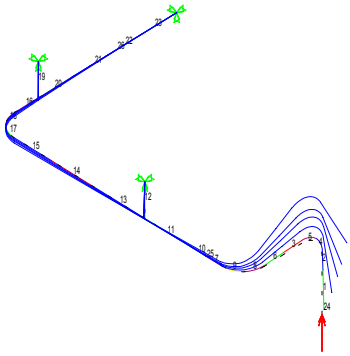

Figure 5 – Case 2a – Free Whip within 50 ms

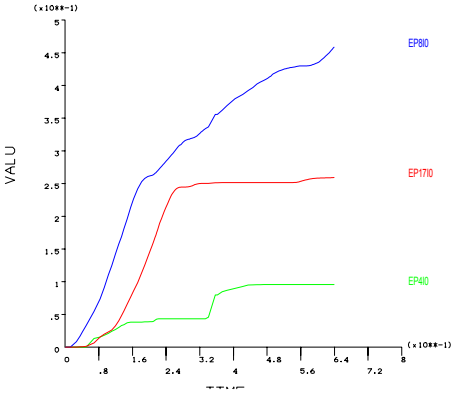

Figure 6 –Case 2a – Plastic Strain at Elbows

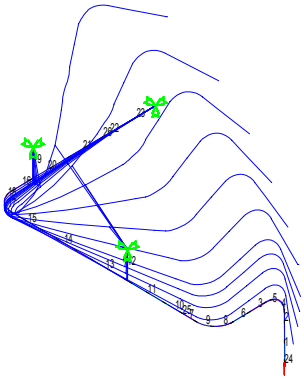

Figure 7 – Case 2f – Free Whip within 538 ms

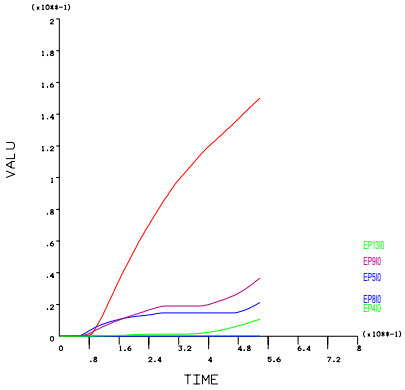

Figure 8 –Case 2f – Plastic Strain at Elbows

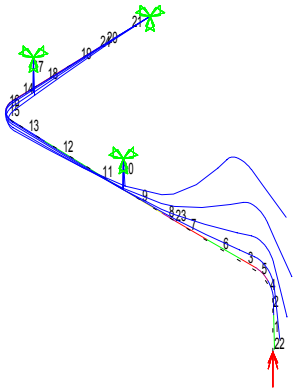

Figure 9 – Case 3 – Free Whip within 88 ms

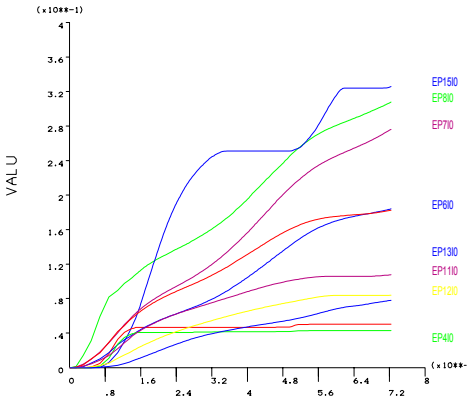

Figure 10 – Case 3 – Plastic Strain in Second Run

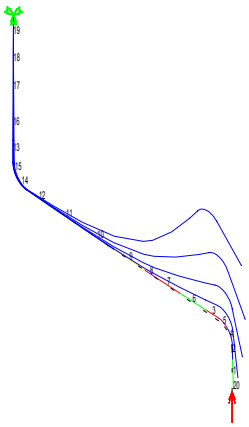

Figure 11 – Case 4 – Free Whip within 91 ms

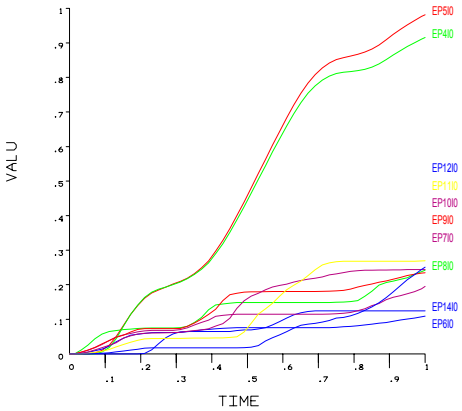

Figure 12 – Case 4 – Plastic Strain in Second Run

Table 2 – Free Whip Investigations – Synthesis of Main Results

Case	F_b (kN)	L (m)	M_{LIM} (kN·m)	M'_p (kN·m)	t_{PH} (ms)	L_{2r} (m)	L^*_h (m)	$L_{h\,2}$ (m)	$L_h{}'_2$ (m)	$L_{h\,3}$ (m)	$L_h{}'_3$ (m)	Notes
1	708.3	7.08	286.1	482.7	13.1	2.76	2.76	0.40	0.67	4.54	6.14	Plastic hinge at first elbow moving to second one
2.a	2267.	1.61	1152.	1943.	12.5	1.97	1.97	0.51	0.86	2.92	4.15	Plastic hinge at second elbow
2.b	1818.	1.61	1152.	1943.	14.2	1.97	1.97	0.63	1.06	3.38	4.85	Plastic hinge at second elbow
2.c	10000	1.61	1152.	1943.	<11.	1.97	1.97	0.12	0.20	1.18	1.60	Plastic hinge at second elbow
2.d	200.	1.61	1152.	1943.	112.	1.97	10.4	5.76	9.72	18.5	29.4	Plastic hinge at third elbow
2.e	1000.	1.61	1152.	1943.	25.5	1.97	1.97	1.15	1.94	5.12	7.56	Plastic hinge at second elbow
2.f	400.	1.61	1152.	1943.	52.1	1.97	10.4	2.88	4.86	10.3	15.9	Plastic hinge at second elbow moving to third one
3	2267.	1.61	1152.	1943.	14.4	10.4	3.88	0.51	0.86	2.92	4.15	Plastic hinge at second run moving to second elbow
4	2267.	1.61	1152.	1943.	14.4	10.4	3.88	0.51	0.86	2.92	4.15	Plastic hinge at second run moving to first elbow

Table 3 – Effective Mass, Kinetic Energy and Velocity at Impacting End

Case	Time History Analysis							Energy Balance Method							
	M_i (kg)	t (s)	δ_{1e} (m)	L_{1e} (m)	θ (rad)	V_{1e} (m/s)	E_{kin} (kN·m)	M_i (kg)	F_b (kN)	L_h (m)	M_p (kN·m)	E_{kin} (kN·m)	I_{AR} (kg·m^2)	ω (rad/s)	V_{1e} (m/s)
1	1714.	52.	0.40	2.27	0.177	16.8	262.5	1829.	708.3	3.25	482.7	362.8	13616.	7.30	23.7
3	1331.	30.	0.44	3.20	0.137	31.7	1008.	1592.	2267.	4.15	1943.	1151.	24447.	9.70	40.3
4	1371.	33.	0.54	3.20	0.169	35.2	1247.	1592.	2267.	4.15	1943.	1420.	24447.	10.78	44.7

Considerations upon Results

The comparison of results from time history or simplified analysis suggests the following main considerations:

A) Plastic Hinge Location and Pipe Whip Plane

Table 2 results show that Equation (3), from Energy Balance Method, provides a conservative approach for the plastic hinge length, which is always greater than issued in Time History Analysis, apart from case 2.c (for a very large jet thrust force). The better approach is found for simple layout (cases 3 and 4), while an over-conservatism may result in cases with long broken runs (as in case 1). On the other hand, calculated lengths through Equation (2), from the Static Analysis Approach, can usefully assess a bottom limit for an unsupported pipe length to accommodate a plastic hinge.

The time history analysis has confirmed that elbows (for their flexibility) are favourite locations for plastic strain accumulation (see cases 2). For large deflections, the plastic hinge tends to move to adjacent elbows, even if starting on a straight run, as seen in cases 1, 2.f, 3 and 4. This movement, which may be far greater than appreciable through Equations (2) or (3) when replacing M_p by M'_p (see $L_h{}'_2$ and $L_h{}'_3$), is in accordance with accumulated experience on pipe whip and depends not only on the considered jet thrust force, but also on the piping layout and supports.

Time history results show that the plastic hinge rise and the free whip evolution are faster for higher jet thrust forces. All considered methods confirm that the span distance required for the hinge development reduces as thrust increases.

As a conservative overall criterion arising from Table 2 results, the main hinge may be assumed at the first change of direction after length $L_h'_2$. If this location is at a distance from the jet axis quite greater than $L_h'_3$ (as in cases 3 and 4), the main hinge length may then be taken equal to $L_h'_3$. This rule was adopted for Cernavoda 2 pipe break analysis.

As to whip plane, the cantilever whip mechanism of Figure 1 is adequately conservative as regards the movements in the plane of break end and second run. The whip maximum reach in this plane is found by assuming a free pivoting around the hinge of the whole-rectified length from break to second elbow. But pipe free whip occurs strictly in this plane only for planar layouts (as in case 4) and out-of-plane movements can be quite significant for cases with long runs after the postulated break or for long unsupported pipe lengths with moderate jet thrust forces (see Figures 3 and 7). Good estimates of the real motion can only be given by time history detailed calculations. A rough overall envelope should assume a spherical motion around the main hinge of the rectified pipe length from the break to the hinge itself.

B) Impact Mass, Kinetic Energy and Velocity at Whipping Ends

As regards the effective impact mass, Table 3 gives a comparison between time history and Equation 4) evaluations at the early plastic hinge development times (from Table 2). The simplified approach provides an acceptable and always conservative estimate, if the plastic hinge length is drawn from Equation (3): over-conservatism due to piping layout with short second runs (like case 1) may be removed by assuming a main hinge at the second elbow.

A good agreement is also verified between time history results and Equations (5), (6) estimates of kinetic energy and velocity at whipping ends. Conservatism, here again on the side of energy balance simplified methods, is mainly due to conservatism inherent in formulations used for the evaluation of plastic hinge length.

It is finally observed that impact mass and velocity estimates may be used to assess maximum impact loads on potential targets near the postulated rupture, by means of Equation (7).

SUMMARY AND CONCLUSION

The whip response following a postulated pipe rupture depends in a complicated way on jet thrust force, piping layout and location of restraints near the break. However, for an unrestrained piping, an acceptable estimate of maximum whipping pipe displacements and impact loads on safety-related potential targets may be based on conservative assumptions about the main plastic hinge location. A whip plane may be defined only for planar layouts between break and first restraint; otherwise, significant displacements are to be expected in any direction, within a range roughly enveloped by the rectified pipe length between the postulated break and the assumed plastic hinge.

As a general conclusion, the Time History analysis of the free whip response following a postulated break in high-energy piping systems has confirmed that the potential pipe whip effects can generally be anticipated in a conservative way through simplified methods based on Static Analysis and Energy Balance.

ACRONYMS AND NOTATIONS

NPP = Nuclear Power Plant
BOP = Balance of Plant
A_e = exit area at break
P_0 = initial pressure at source
P_a = ambient pressure
T_D = piping design temperature
E = material Young's elastic modulus
E_p = material plastic modulus
S_y, S_u = material yield and ultimate strengths
r_i, r_0 = inside and outside radii of pipe
t_w = pipe wall thickness
Z_e = pipe section elastic modulus = $\pi (r_0^4 - r_i^4) / r_0$
Z_p = pipe section plastic modulus = $4 (r_0^3 - r_i^3) / 3$
δ = free-end displacement
θ = rotation of the whipping pipe
I_{AR} = moment of inertia around the plastic hinge
ω = V/L = angular velocity around the hinge
K = stiffness of impacted structure or component

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