A multi-step approach for evaluation of pipe impact effects

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1 INTRODUCTION

The licensing of new and requalification of existing plant requires the consideration of effects arising from postulated breaks in high-energy lines. If the resulting jets or whipping pipes affect equipment or components (with safety-related functions in relation with the postulated break), their structural integrity and functionality has to be guaranteed. This can be achieved either by demonstrating sufficient ruggedness, or by obviating the problem with hardware (restraints, screens, deflectors, etc). The present paper is orientated towards the first solution.

A methodology has been developed and applied to the requalification of high-energy piping at the Santa Maria de Garoña NPP in Spain. It provides techniques for evaluation of pipe-whip and jet effects on various structures inside the containment: containment liner, pedestal, shield wall, pipes and penetrations. Items of little structural strength (such as cables, conduits, etc) were excluded from this approach for obvious reasons.

The methodology developed decomposes the evaluation efforts in various levels of decreasing conservatism and increasing complexity and cost. Higher evaluation levels are applied only to interactions where lower levels fail and where there is a reasonable expectation that more realistic analyses might demonstrate acceptability. The evaluation levels are described in this paper for pipe-on-pipe impact interactions. This case has been selected because it is common to all plants and because, from the information presented, other applications (targets other than pipes, jet forces rather than impacts) are relatively straightforward.

2 GENERAL METHODOLOGY

Advances in computer hardware and software have for some time allowed conducting three-dimensional calculations of pipe-on-pipe impact (see, for example, Marti et al, 1983; Mackay et al, 1984). However, that process is expensive and very often unnecessary. Hence, the emphasis must be placed
in finding simplified, yet conservative, procedures which allow reserving full 3-D analyses for the cases in which they became unavoidable.

Many researchers have worked on such simplified procedures (see, for instance, Enis et al, 1980; Clendening et al, 1983; Prinja et al, 1984) but the complexity of the problem and number of variables of interest make it difficult to arrive at solutions of generalised usefulness.

The essence of the lower level procedures proposed here is the assumption that the effective missile energy is dissipated plastically in the interaction. The effective energy of the missile is defined as the part of its kinetic energy which corresponds to the velocity change effected by the impact. The assumption can be formulated as follows:

\[ E = \int_0^d F(x) \, dx, \]

where \( E \) is the effective missile energy, \( F(x) \) is the force of interaction developed as a function of the relative missile-target displacement \( x \), and \( d \) is the relative displacement for which \( E \) is dissipated.

The structural survivability of the target is then assessed judging whether it can successfully sustain \( F(d) \) as a static load. The method is conservative but is useful for quick dismissal of many safe interactions.

The procedure hinges on the determination of \( F(x) \), that is, the function relating the forces developed to the interpenetrations produced. The derivation of \( F(x) \) is discussed in the next section for the case of pipe-on-pipe impact.

3 DETERMINATION OF \( F(x) \) FOR PIPE-ON-PIPE IMPACT

When considering the collapse of a pipe, two different mechanisms contribute relative displacements (see Fig.1):

1. Local collapse, which occurs as a progressive ovalisation of the section directly involved; its occurrence is unrelated to possible displacements of the pipe axis.

2. Structural collapse, which appears as a progressive displacement of the pipe axis from its initial position; such deformations may occur independently of whether the local section changes shape are not.

The two mechanisms clearly operate in series. As a first approximation they can be considered to be mutually independent. There are however some cross-influences, eg: large ovalisations facilitate the formation of a structural hinge at that location; and large axis displacements require some ovalisation to take place.

Notice that, although local collapse will not occur in a pipe of greater schedule, structural collapse might take place if the combination of dimensions is adequate for it. In that sense, the "equal schedule argument" for qualifying pipe-on-pipe impact events need not be conservative in all cases.

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3.1 Local collapse

Following the Enis et al (1980) approach, built on the experimental results of Pech et al (1977), local collapse can be represented with an expression of the type:

\[ F = F_0 + Kx, \]

where \( F_0 \) and \( K \) are functions of the pipe dimensions and material characteristics. The equation neglects initial elastic deformations and is depicted in Figure 2.

The values of \( F_0 \) and \( K \) are derived based on semiempirical correlations which include the hypothesis that local collapse is resisted by two additive mechanisms:

a) ring crushing, which generates a force proportional to the crushed length

b) strengthening contributed by the rest of the pipe outside the crushed length, an effect which is independent of the crushed length.

The detailed expressions can be found in the referenced paper. Local deformations must be bound by a limit of what is admissible. Based on experimental results (Clendening et al, 1983) and analytical considerations (Prinja et al, 1984), it seemed appropriate and conservative to limit local collapse to decreases in the section diameter below 30%.

3.2 Structural collapse

From the viewpoint of structural collapse, a pipe can be considered as a beam provided with some support conditions and subjected to a concentrated load. As the load increases, elastic deformations form until a first plastic hinge develops. This produces a knee in the force-displacement relationship which describes structural collapse.

Further increases in the load result in activation of hardening at the hinge and, eventually, in the formation of a second hinge. The process continues until unacceptable plastic strains occur at one of the plastic hinges formed. Based on licensing precedents, the maximum acceptable strain was conservatively taken as 45% of the ultimate uniaxial tensile strain of the material.

The mathematical details are omitted here for lack of space but they are not too difficult to derive, possibly with the exception of the incorporation of hardening. Figure 3 presents a typical force-displacement representation of structural collapse.

3.3 Combination of effects

The local and structural collapse mechanisms of both missile and target pipes act as non-linear springs operating in series. At each value of the force \( F \), the global tangent stiffness is:
(3) \[ K = \frac{1}{E(1/K_i)} \]

where \( K_i \) is the tangent stiffness of mechanism \( i \) at that value of the force.

This combination procedure permits generating a force-displacement relationship \( F(x) \), as sought, for representing the energy dissipation characteristics.

4 EVALUATION OF INTERACTIONS

The above relationship can then be applied to the qualification of pipe-on-pipe interactions. If the dissipation of the effective kinetic energy exceeds one of the allowable limits, the interaction cannot be qualified. Those limits are imposed to local deformations (section 3.1), structural deformations (section 3.2) and, possibly, to losses in cross-section of the target pipe if it must maintain its function past the impact even.

Three-dimensional non-linear dynamic analyses were conducted to confirm the above procedures and indicated that the ability to dissipate energy was being underestimated. Actual values were at least 30% and, possibly, as much as 100% greater than calculated.

The proposed procedure was used as a first level qualification tool. It led to the immediate qualification of about 80% of the almost 400 interactions resulting from high-energy line breaks that required structural assessment inside the containment of Garoña NPP.

When interactions could not be qualified in this way, the margin of exceedance was sufficiently small, progressively more sophisticated approaches were utilised, including 3-D dynamic calculations.

An example of the latter can be seen in Fig. 4. It is an 8in Sch80 pipe continuously supported along two generators 106° apart and impacted by a 10in Sch100 missile. The analysis was carried out with FR3D. The figure shows the deformations of the target pipe when a 40% decrease of the diameter had been reached.

It is interesting to mention that the combination of the above procedures, together with detailed safety analyses of the Garoña plant, allowed evaluating all interactions resulting from high energy breaks inside containment without recourse to hardware modifications.

5 CONCLUSIONS

A flexible procedure was developed for evaluation of interactions resulting from postulated high-energy line breaks inside containment.

The procedure includes steps of increasing sophistication. It starts with inexpensive energy dissipation assessments for very safe interactions and proceeds to 3-D non-linear dynamic analyses when warranted.

The simplest approaches allowed qualification of 80% of interactions at Garoña NPP. The implementation of the pro-
cedures proposed here, combined with detail safety analyses of the plant, permitted qualifying all resulting interactions without impinging plant design changes.

REFERENCES


Fig. 1 Pipe collapse mechanisms a) local b) structural

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Fig. 2 Force displacement relationship for local collapse. Displacement limited to 30% of diameter

Fig. 3 Force displacement relationship for structural collapse. Limited by development of 45% of ultimate strains in a hinge

Fig. 4 Deformations of longitudinally supported target pipe after loss of 40% of local diameter