Analysis of Pressure Transients and Cavitation in a Distributor

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Abstract*: During pressure testing of a large distributor the weld securing the bulkhead failed, which triggered large pressure transients and cavitation phenomena. The problem has been studied by explicit integration, using shell elements for the structural parts and acoustic elements for the water. Although the calculations had to be carried out in the absence of any information about the outcome of the accident, very good consistency was achieved between the predictions and the actual observations.*

Keywords*: Dynamics, Cavitation, Fluid-Structure Interaction, Distributor.*

1. Introduction

In a hydroelectric power plant, the penstock distributor is a piping structure that distributes the pressurised water to the various turbine groups. In the case studied here, four such groups existed, located at the end of the four legs of the distributor.

In the case studied here, during pressure testing of the distributor, the weld securing the bulkhead underwent a sudden failure. This caused large pressure transients in the water, thus giving rise to dynamic loads in the distributor, with the associated stresses and displacements.

The bulkhead was only a temporary feature, provided for conducting the pressure test. However, since that failure and the ensuing transients were unforeseen, a question arises as to the deleterious effects that the distributor might have undergone as a consequence of the accident, affecting its current state and future serviceability. For studying this matter, a dynamic characterisation of the distributor will first be produced via its natural modes and frequencies and then the transient response of the distributor will be analysed.

2. Description of the problem

2.1 Distributor

The geometry of the distributor appears in Figure 1; although the details are not shown here, different parts of the distributor have different thicknesses. The material is DILLIMAX 690 E steel and the properties used in the analyses are density 7850 kg/m^3, Young's modulus 210 GPa, Poisson's ratio 0.3, elastic limit 670 MPa, ultimate stress 770 MPa, and ductility 0.10.

The final stretch of the four legs of the distributor is embedded in concrete over a length of 6 m, which can be considered to remain fixed at all times. Additionally, the distributor rests on 12 low friction supports with a theoretical friction coefficient of 0.15; as this value seems high for PTFE surfaces, some calculations will also be carried out assuming a frictionless contact.

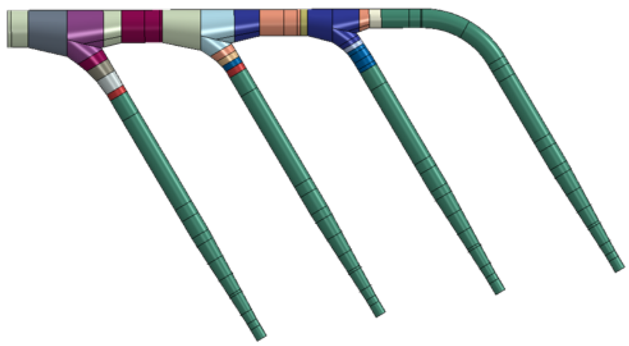

Figure 1. Geometry of the distributor.

The masses of the supports that move together with the distributor were incorporated in the model, though they only amount to about 6% of the total mass. The vertical loads acting on each of the 12 supports were known and taken into account when assessing frictional sliding.

2.2 Hydrotest and incident

To ensure the serviceability of the distributor, a hydrotest was to be conducted. For this purpose a bulkhead was welded at the upstream end of the distributor and the contained water would have been pressurised up to 11 MPa. However, when the water pressures reached 6.26 MPa the weld securing the bulkhead underwent a brittle failure, leading to a sudden depressurisation of the immediate region. This triggered a reverse water hammer, with ensuing rapid changes in the water pressures and velocities which excited a transient response of the structure of the distributor.

From the viewpoint of the boundary conditions at the upstream end of the distributor, the failure entails consequences for both the structure and the water. Just before the accident the inlet section of the distributor was being subjected to longitudinal tensile forces of 8.5 MN/m as a result of the pressures exerted by the water on the bulkhead; from the instant of failure, the longitudinal stresses vanish at the upstream end of the distributor. In the water the consequences of the failure are analogous: the water pressures, which prior to the accident were 6.26 MPa throughout the distributor, vanish at its upstream section from the instant of failure onwards.

3. Simulation approach

It is beyond the scope of the present paper to discuss the literature dealing with cavitation and column separation, but interested readers may wish to peruse the review of the state-of-the-art produced by Bergant, Simpson and Tusseling (2006).

The methodology adopted here intends to represent, as accurately as possible, the transient event that took place, which consists of a reverse water hammer triggered by the loss of the bulkhead. The initial conditions are water pressures of 6.26 MPa and the associated stresses in the distributor.

The accident then imposes new boundary conditions at the upstream end, which consist in zero longitudinal stresses in the steel and zero pressures in the water. As a consequence, a wave will start travelling downstream in the water, leaving behind zero pressures and water velocities of about 6 m/s towards the upstream end of the distributor. With a thickness to diameter ratio on the order of 0.01, the wave travels at about 1000 m/s.

This wave will bifurcate at the various branching points of the distributor, from which partial rebounds will take place, and eventually reach their corresponding ends. When attempting to rebound as a tensile wave, strong cavitation phenomena must be expected to occur at the ends of the four legs. This will be followed by water column separation and subsequent implosions, which also need to be adequately modelled. Apart from the wave in the water, waves will also travel in the steel structure with a velocity slightly above 5 km/s; they are originated by the sudden disappearance of the longitudinal tensile stresses at the inlet section of the distributor.

To simulate all these phenomena in a realistic fashion, the approach adopted was to carry out a coupled analysis of the structural and fluid problems by explicit integration. Shell elements were used to represent the steel and acoustic elements for the water, with an equation of state allowing them to compress and cavitate as required. The use of acoustic elements may introduce some distortions in the solution at long times, as it obviates water losses through the inlet section, but it provides a good approximation for shorter times, which is when the peak effects occur.

In an explicit integration process, the solution at each time step is obtained by direct integration of the equations of motion, hence it is never necessary to solve a coupled system of equations. The drawback is that explicit integration is only conditionally stable and Courant's stability condition must be satisfied, which Abaqus/Explicit automatically does.

The simulation uses the fluid cavitation capabilities available in Abaqus/Explicit through the option *ACOUSTIC MEDIUM, CAVITATION LIMIT. The equation of state corresponds to the maximum of the elastic pressure, obtained multiplying the bulk modulus by the volumetric strain, and a limiting pressure specified by the user. Thus, the acoustic medium loses all its material stiffness under cavitation. The implementation allows the fluid to recover its stiffness suddenly when the elastic pressure is greater than the specified threshold, i.e. when the material has been recompressed following the expansion that led to cavitation. This approach is sufficiently accurate for the study here documented.

3.1 Geometry and meshes

Using the geometrical information shown, finite element meshes were generated to represent the distributor and the contained water. Figure 2 shows the global mesh representing the steel structure. The elements used are linear quadrilateral reduced-integration shell elements (S4R). The assigned thicknesses reproduce the actual ones in the distributor.

Likewise, a mesh was generated to represent the water; the local close-up in Figure 3 gives an idea of the degree of refinement. Linear tetrahedral acoustic elements (AC3D4) were used to represent the water in the model. The typical average dimension of the elements used, both for the steel and the water, is 50 cm. The complete model comprises about 11,000 shell elements representing the steel and about 145,000 acoustic elements for the water.

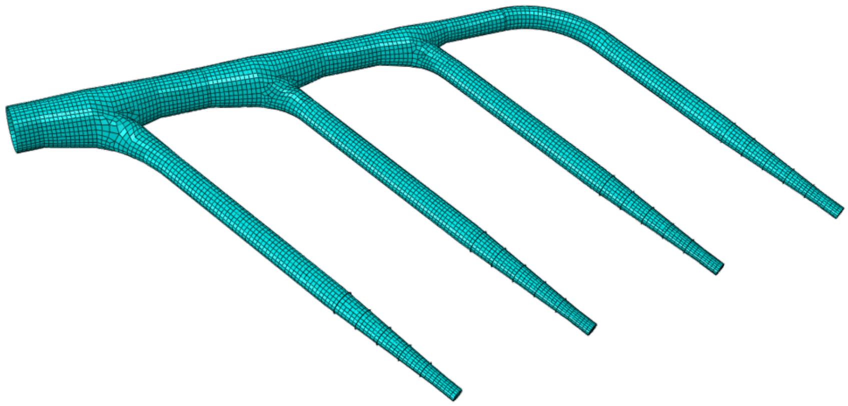

Figure 2. Mesh of the distributor.

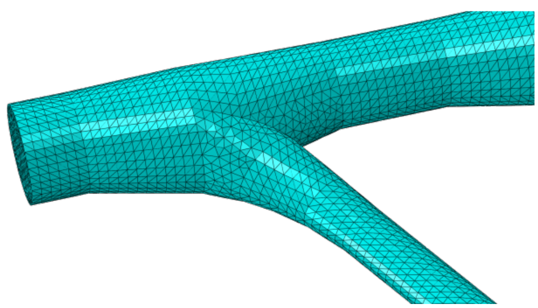

Figure 3. Detail of the acoustic mesh.

3.2 Boundary conditions

From the viewpoint of the structure the boundary conditions to be applied in the calculations are essentially the fixed stretches of the distributor legs and the 12 low friction supports.

Gravity was not defined in the model, as the associated displacements and stresses are negligible compared to those produced by the accident. However, the appropriate vertical forces were introduced in the low friction supports to account for their frictional behaviour. Also, the initial water pressures were specified to capture any differences in cavitation behaviour, though the calculations eventually showed this hydrostatic effect on cavitation was not significant.

The support saddles were not meshed, rather the surfaces involved were kinematically coupled (with rigid body motion) to their respective reference nodes, representing the saddle over the sliding plane and including a mass element. The reference nodes of the end supports were encastre; for the rest of the supports, only the vertical movements were prevented and a frictional contact was defined to govern sliding on a horizontal plane.

The boundary conditions at the inlet section are different when reproducing the preexisting situation in the distributor and that prevailing after the accident starts. Prior to the accident, the steel was undergoing the longitudinal tension required to balance the water pressures exerted on the bulkhead; similarly, the water boundary condition was a fixed pressure of 6.26 MPa. The accident is modelled by cancelling both the longitudinal stress in the steel and the water pressure.

3.3 Materials

The steel was characterised as an elastoplastic material with linear hardening, with the properties given earlier. The water was described as an acoustic material with a density of 1000 kg/m^3 and a compressional wave velocity of 1500 m/s. Cavitation is assumed to take place in the water if the relative pressure reaches -0.1 MPa. Hydrostatic pressures in the distributor are taken into account, allowing the upper part of a section to cavitate earlier than the lower part.

No material damping was introduced in the behaviour of either the steel or the water.

4. Analysis of the distributor

4.1 Natural frequencies

To understand the dynamic response of the structure, the natural modes and associated frequencies are first determined. The more relevant conditions, given that the final purpose of the study is to analyse the accident sequence, are those in which the accident took place but, in order to obtain more complete information, some other conditions have also been analysed.

The first condition studied, simply for the sake of reference, is that of the distributor subjected to the same boundary conditions of the hydrotest but without water. The results presented in Figure 4 for the first 6 modes show that the first mode has a natural frequency of 0.86 Hz and involves a global displacement of the distributor and bending of the four distributor legs. Subsequent modes arise at much higher frequencies and are associated with the bending of one or more legs or with the local expansion of the inlet section.

The second analysis includes the water inside the distributor, which only contributes mass to the structure, thereby reducing its natural frequencies. In this analysis, though, the water was still unpressurised; water pressures naturally tend to stiffen the behaviour of piping structures. The natural modes are not shown because they change little, but the corresponding frequencies decrease by almost a factor of 2. The first mode now has a frequency of 0.48 Hz.

Finally, the situation of greater interest was studied, which is that of the distributor with water at 6.26 MPa, which was the pressure at the time of the accident. In this situation the first 6 modes of vibration, together with their frequencies, are shown in Figure 5. The stiffening effect of the water pressure leads to a frequency increase of about 10% in the lower modes. The first mode has now a frequency of 0.53 Hz, but there is still a factor of about 5 to the next natural frequency, hence most of the energy of the excitation can be expected to be taken up by the first mode.

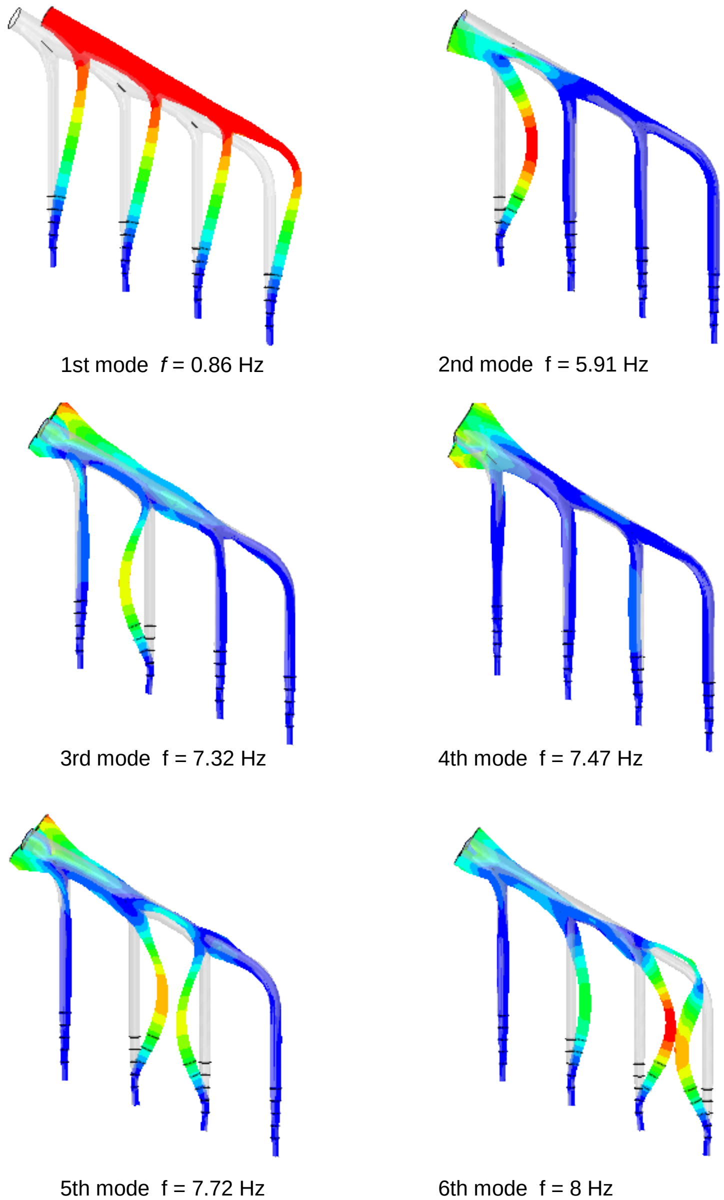

Figure 4. First modes of the structure without water.

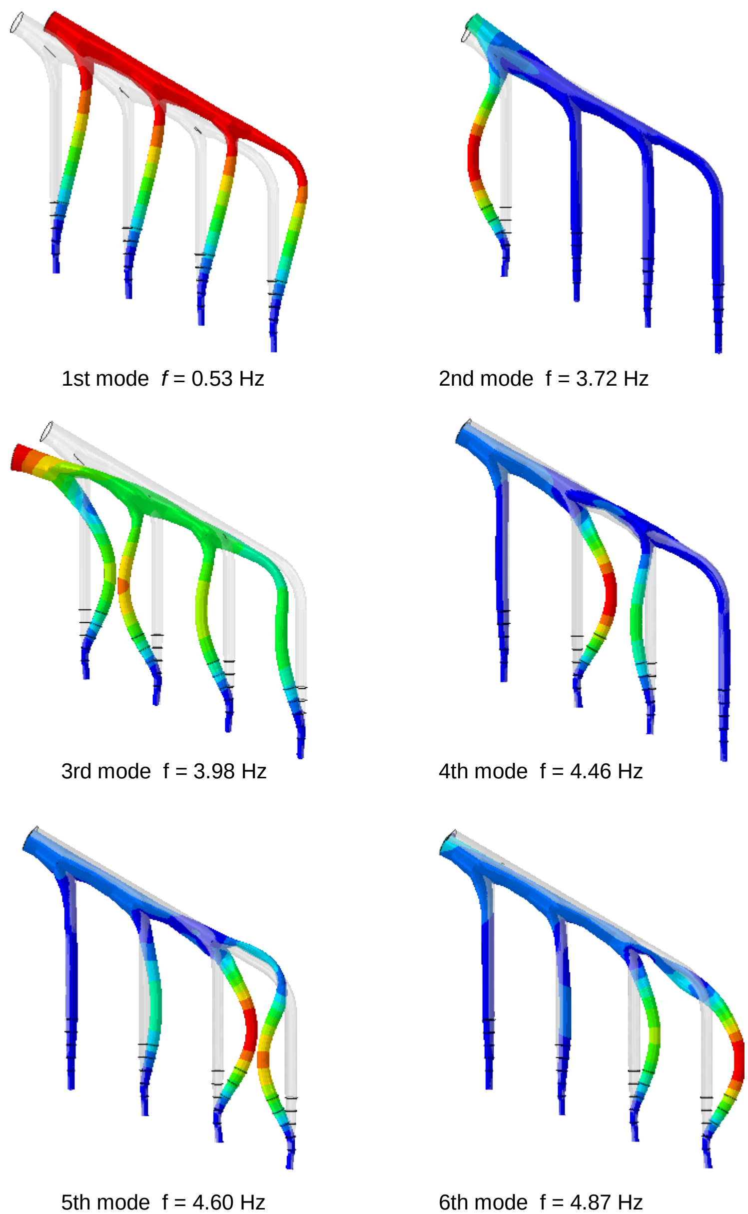

Figure 5. First modes of the structure with water at 6.26 MPa.

4.2 Transient response

Before analysing the transient response of the distributor to the dynamic excitation generated by the accident, it is necessary to arrive numerically at the initial conditions that existed prior to the accident. This analysis was carried out by slowly applying a pressure of 6.26 MPa in the water contained in the distributor to ensure that an essentially static configuration had been achieved prior to starting the analysis of the transient. The resulting displacement amplitudes are shown in Figure 6 and the von Mises stresses in the steel structure are plotted in Figure 7.

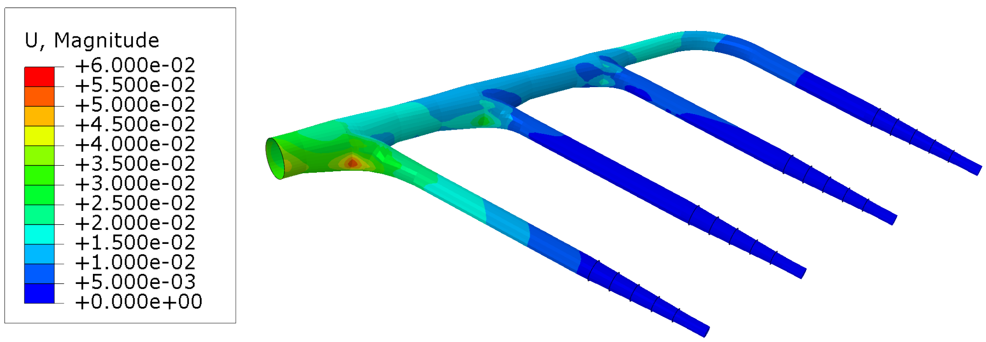

Figure 6. Displacements under pressure of 6.26 MPa (m).

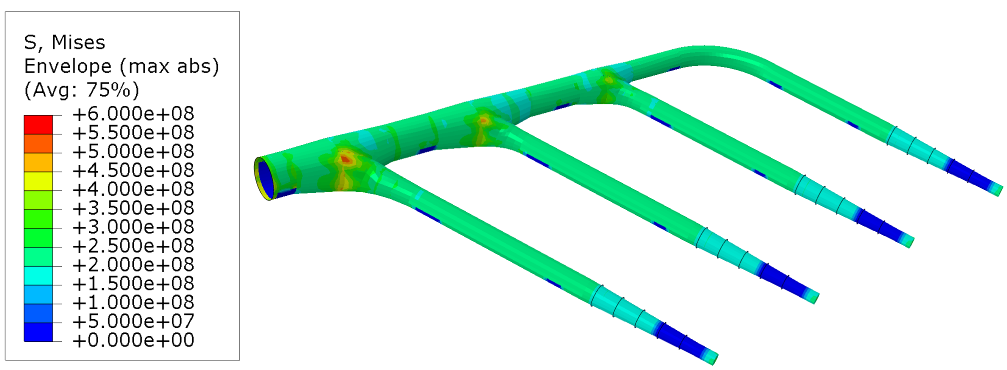

Figure 7. Stresses under pressure of 6.26 MPa (Pa).

It is from that essentially static, reference initial state that the accident analysis starts. This simply consists in suppressing the bulkhead, thereby cancelling any longitudinal stresses in the inlet section of the distributor, and cancelling also the water pressures at that same section. The friction coefficient is assumed to be 0.15 at all the supports, but this value will be revisited later.

Figure 8 shows the water pressures 50 ms after the onset of the accident. The depressurisation of the water can be seen to extend to different points along all four legs of the distributor. The stresses generated in the distributor at that same time appear in Figure 9; they already show the first consequences of bending of the four legs, with their final 6 m fixed.

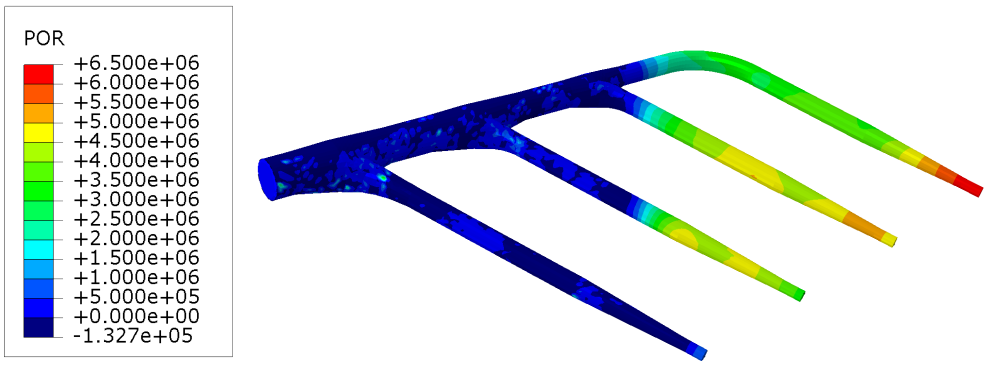

Figure 8. Pressure after 50 ms (Pa).

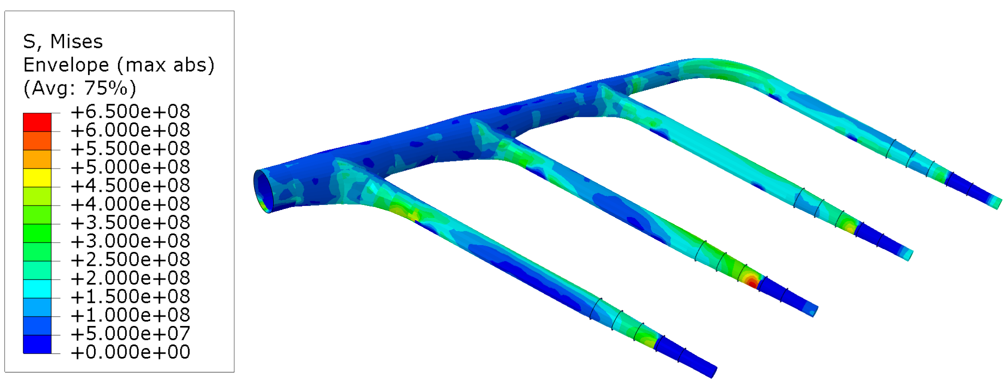

Figure 9. Stresses after 50 ms (Pa).

After the bulkhead is lost, there is communication between the inside of the distributor at 6.26 MPa and the outside at 0 MPa; this causes water to start exiting the distributor with a velocity of about 6 m/s. However, once cavitation occurs, the flow is slowed down because the inner pressures at the cavitating points approach -0.1 MPa. Eventually that leads to the vapour volume collapsing and to the generation of new transient pressures either by impact between two separated water columns or by impact of a column against the end of one of the distributor legs.

The latter is the first phenomenon to occur, as the water column hits F7, the end of the first leg of the distributor, 4.8 s after the onset of the incident. The water pressures at that point, shown in Figure 10, clearly evince this event; the associated stresses in the distributor appear in Figure 11.

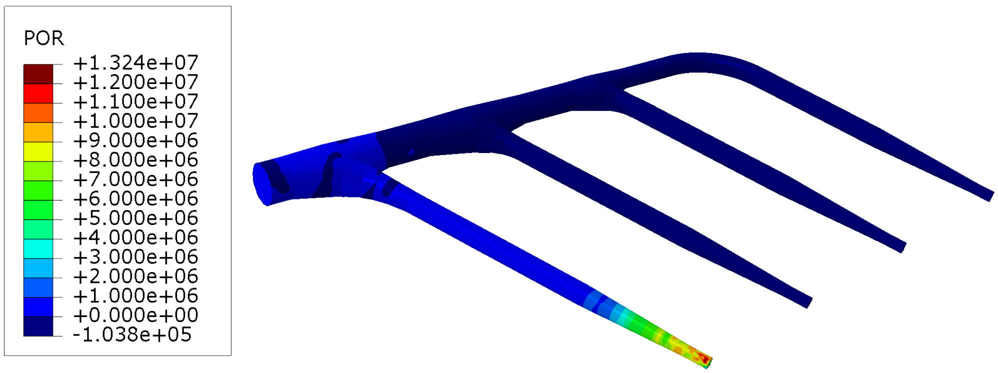

Figure 10. Pressures after first implosion at 4.8 s (Pa).

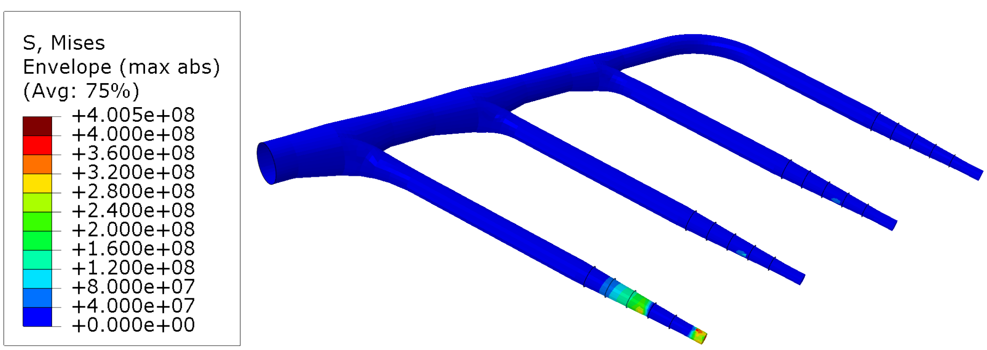

Figure 11. Stresses after first implosion at 4.8 s (Pa).

The sequence described earlier is repeatedly indicated in Figure 12, which presents the pressure histories at the end points of the four legs of the distributor. As already mentioned the first spike shown corresponds to the collapse of the vapour bubble at F7 at 4.8 s; the corresponding spikes at the other leg ends can be seen to follow.

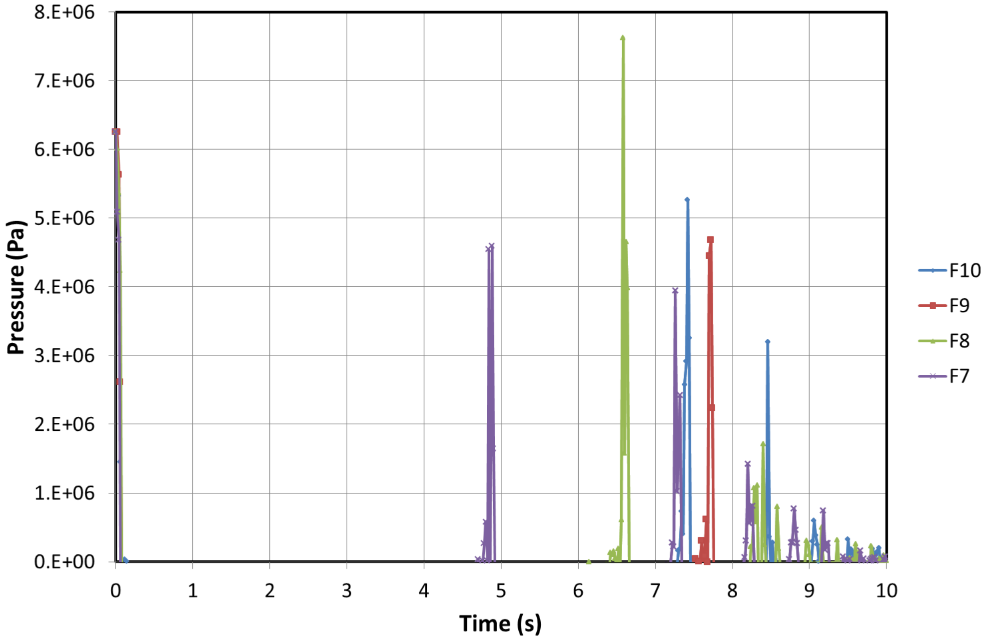

Figure 12. Pressure histories over the first 10 s.

A particularly illustrative plot is perhaps that provided by Figure 13, where the pressure and displacement plots are superimposed. It clearly confirms that the various displacement jumps are caused either by the initial incident or by the subsequent implosions of collapsing vapour bubbles. In this figure there is no relation between the origins of the two ordinates plotted together.

The largest component of the displacement is transverse to the direction of the four distributor legs and the maximum value occurs 0.3 s after the onset of the accident. This time has therefore been selected for showing the displacement magnitudes (Figure 14), which are on the region of 50 cm for all the main stretch of the distributor. The displacements peak again, this time in the opposite sense, when the time reaches 1 s.

It is also of interest to observe the displacements at the plateaus in the displacement histories that appeared in Figure 13. The maximum displacements at those times turn out to be only on the order of very few cm or less, which indicates that, following the transient displacements, the distributor essentially returns to its original location, as the vibrations triggered by the accident activate a largely elastic response.

Along that same line of thought, any damage caused to the distributor would be manifested in plastic strains accumulated during the transient event. The analysis shows that the only points where plastic strains develop are the ends of the four legs of the distributor and, as observed in Figure 15, they are all below 0.7%. Taking all this information into account, it must be concluded that the distributor did not undergo any enduring damage during the accident.

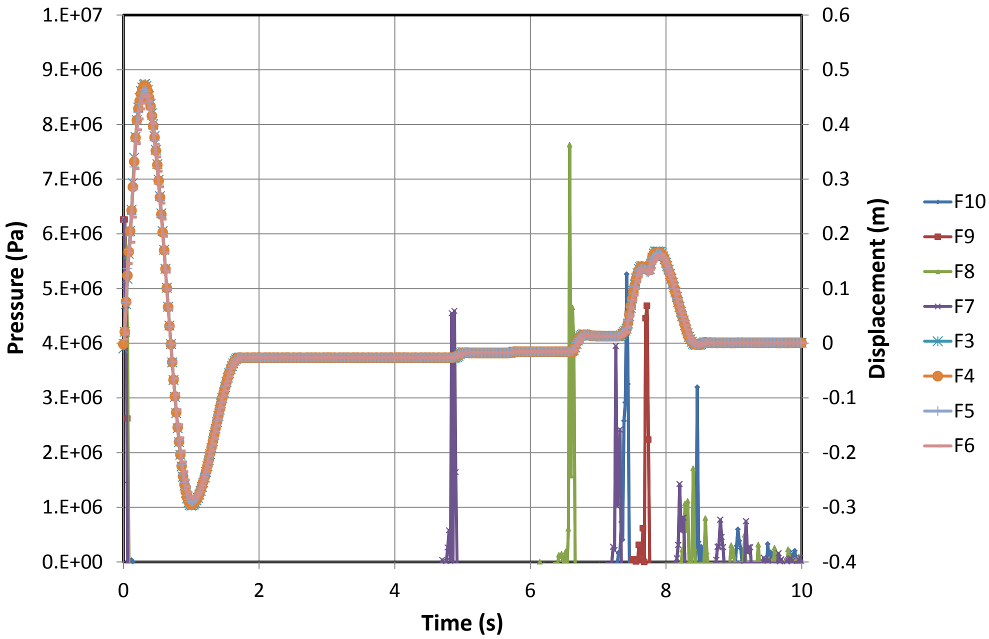

Figure 13. Superposition of pressure and displacement histories.

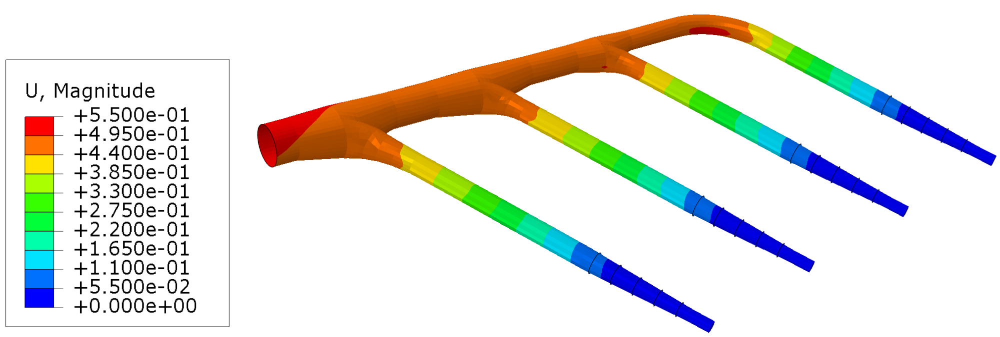

Figure 14. Displacement magnitudes after 0.3s (m).

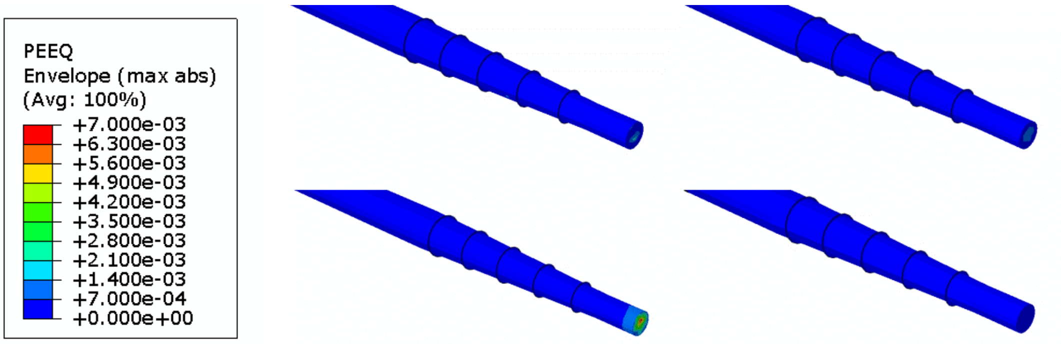

Figure 15. Accumulated plastic strains (-).

Finally, since 0.15 seemed to be a high friction coefficient for a PTFE interface, the calculations were repeated on the assumption of a frictionless contact. In this situation Figure 16 shows the plastic strains at the ends of the four legs, which remain very small, though they are no longer limited to the final plugs of the distributor legs.

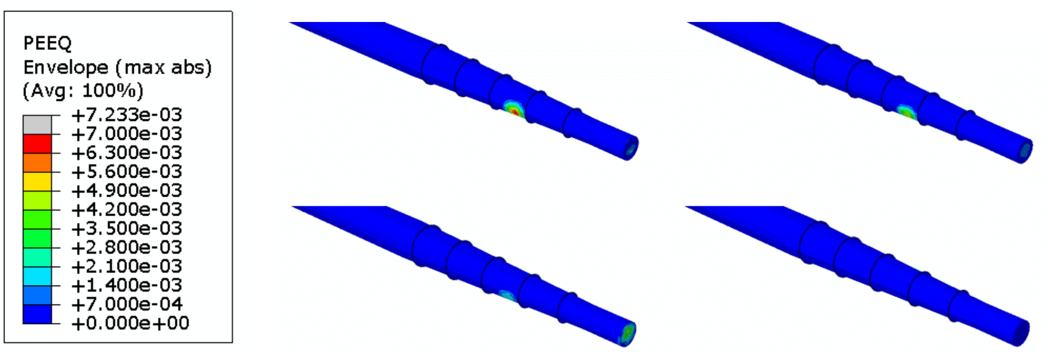

Figure 16. Accumulated plastic strains with frictionless supports (-).

Also, the displacement histories presented in Figure 17 indicate that the peak displacements increase by about 10% with respect to the values attained with a friction coefficient of 0.15 and that, as there is no longer any energy dissipation by friction, the displacements oscillate about the equilibrium position in a more gradual way. Since no material damping had been introduced in the calculations, the decreasing displacements are caused by energy exchanges between the steel and the water, not by material damping.

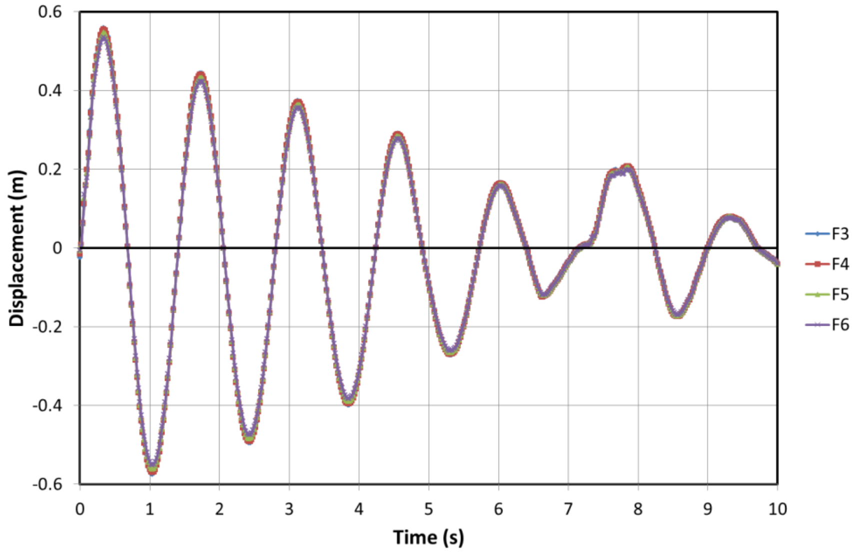

Figure 17. Displacement histories with frictionless supports.

Although no detailed information had been made available at the time of the analyses, it was later confirmed that the calculated sequence of events, the magnitude of the peak and residual displacements, and the extent of yielding were all consistent with the observations.

5. Conclusions

A numerical model was generated to analyse a penstock distributor, which underwent strong pressure transients caused by the failure of the bulkhead during the hydrotest when the internal pressures were 6.26 MPa. The model, using shell elements for the distributor and acoustic elements for the water, was analysed with Abaqus in order to extract the natural frequencies and to determine the transient response during the accident. The ultimate objective of the exercise was to assess the present state of the distributor.

The first conclusion that can be offered is that the combination of shell elements for the structure and acoustic elements for the water proved to be very adequate for modelling this event.

From the viewpoint of the natural frequencies, with water inside at a pressure of 6.26 MPa, the first frequency of the distributor is 0.53 Hz, a period of 1.9 s; this mode corresponds to a displacement of the main conduit with bending of its four legs. When filled with unpressurised water, the frequency decreases to 0.48 Hz; if empty, it grows to 0.86 Hz.

The transient is governed by the dynamics of the reverse water hammer triggered by the failure of the bulkhead, which causes fast travelling changes in the water pressures and velocities.

The peak displacements occur during the first cycle of response, 0.3 s after the onset of the accident, and attain values on the region of 50 cm. The peak values would grow by about 10% if the distributor is assumed to rest on frictionless supports, rather than with the friction coefficient of 0.15 employed here.

At the end of the initial transient pulse the peak residual displacement is only 26 mm. For structural purposes, those displacements can be considered negligible.

The peak pressures developed during the transient only exceed 12 MPa at the end of the first distributor leg; those pressures arise around 4.8 s after the onset of the accident.

The plastic strains accumulated during the transient are limited to the final plugs of the four legs of the distributor and their values are below 1%. If the supports were frictionless plastic strains appear at other locations, but their values are well below 1%.

As a consequence of the foregoing observations it is concluded that, at least from a purely structural standpoint, the distributor must be considered to remain sound in its present state. However this may not cover other functionality requirements imposed on the distributor.

6. References

1. Abaqus Analysis User´s Guide, Version 6.13, Dassault Systèmes Simulia Corp., Providence, RI.
2. Bergant, A., Simpson, A.R. and Tusseling, A.S., “Water Hammer with Column Separation: A Historical Review”, Journal of Fluids and Structures, vol. 22 no. 2, pp. 135–171, 2006.