Water-filled Bladders, an Innovative Bearing Interface for Arch Dam Bracing

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Abstract

Some existing arch dams can require the construction of a supporting downstream structure to improve their behavior. The bracing structure is generally rigidly connected to the dam, but in some cases the designer can seek a flexible connection that can adapt to the deformation mode of each structure and avoid hard points emergence and stress concentration. This has already been done at Kölnbrein dam in Austria, by the use of rubber pads. The paper presents a new solution to realize a flexible connection, allowing an excellent control of the forces transferred from the dam to its bracing structure. The solution relies on large inflatable jacks hydraulically connected to the reservoir. This EDF-patented solution also affords the distinct advantage of not requiring unloading the dam in order to load the bearings. This solution, based on the use of water-filled bladders, is under development at detailed design stage for a 50 m high arch dam. Some tests will be conducted at the end of 2017 on full scale prototypes (4 m x 11 m x 0,8 m), with a dedicated vertical test bench, in order to qualify bladders' suppliers and check the installation and filling process of the bladders.

Keywords: Arch dam, Support, Bearing, Inflatable, Rubber.

1. INTRODUCTION

Because of their original design – for example arch dams in large valleys – dams are sometimes affected by non-typical behavior, such as unstabilised irreversible displacements. In some cases, these troubles **can necessitate bracing of the dam**. The regulatory evolution, in terms of flood control or seismic protection, can also lead to a need for reinforcement.

A typical solution for bracing an existing concrete dam consists of building a **downstream concrete structure** to help support the dam, which will reduce its displacements as well as the stress applied to its foundation surface. This solution has already been used on dams such as Kölnbrein dam in Austria or Les Toules dam in Switzerland.

In this kind of project, **the control of the load that is transferred from the existing dam to the downstream bracing structure is critical**. Some reinforcement designs, such as Les Toules, require a fully rigid connection between the dam and its reinforcement, in order to make both structures behave as a monolith. In some other cases, such as for Kölnbrein dam where the massive reinforcement structure buttresses the lower section of the existing dam, the connection must be flexible in order to adapt to the deformation mode of each structure, namely the existing dam and the downstream bracing, avoiding hard points emergence and stress concentration. Consequently, the designer of the **Kölnbrein bracing used more than 600 neoprene pads** in order to bear the dam on its reinforcement structure [1]. These pads are mounted on adjustable steel wedges which allow control of the thickness of the bearings before their loading. The bearings developed for Kölnbrein have proved to be effective, but some disadvantages can be highlighted:

- the loads transferred by the neoprene pads depend on their shim adjustment, whose determining requires very accurate modelling. Moreover, the transferrable load is quite limited in the lower part of the dam because of the limited displacements at its toe;
- the loading of the reinforcement, and every modification of the shim adjustment of the pads, necessitate the unloading of the dam by emptying it;
- the monitoring of the actual transferred loads is arduous.

EDF has patented a new concept invented by A. Lochu, which avoids these disadvantages and offers some distinct advantages. The solution allows:

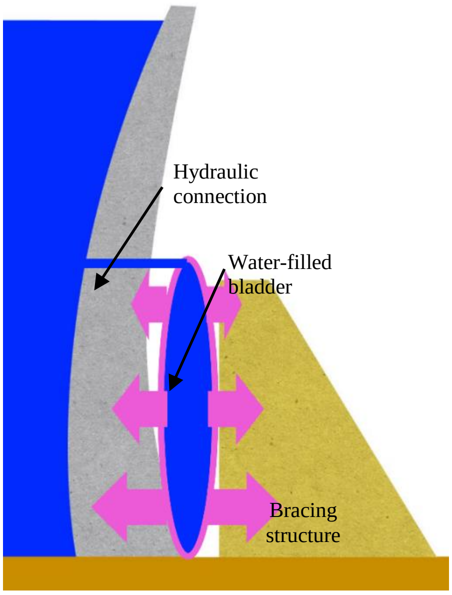
- **an excellent control of the loads applied** between both structures, whatever their relative displacements are;
- **an automatic and passive adaptation of the transferred loads** to the level of the reservoir;

- the loading of the reinforcement structure irrespective of the thermo-mechanical stress state of the dam during its commissioning, which **allows the scheme to continue operating without being dewatered and avoids all the associated costs and environmental impact related thereto**.

2. The Concept

The main idea is to use big **inflatable bladders filled with water** as interface elements between the downstream face of the dam and the upstream face of the reinforcement structure. As shown in Figure 1., the bladders act as jacks, applying opposite forces which only depend on the surfaces and pressures, but not (at first order) on the distance between the bearing surfaces. With this solution, the action of the reinforcement upon a dam is directly controlled in terms of load, and not in terms of displacement, unlike with elastic bearings. This aspect considerably facilitates the numerical modelling of the behaviour of both structures, which can be decoupled (for static loads).

The second point of the concept is that by hydraulically connecting the inflatable bladders to the upstream reservoir, the pressure profiles on the upstream face of the dam and inside the bearing devices are the same (according to the communicating vessels principle, and whatever the fitting level), as shown in Figure 2. The load transfer is thus proportional to the level of the reservoir, and adapts totally passively to the hydraulic upstream load on the dam.



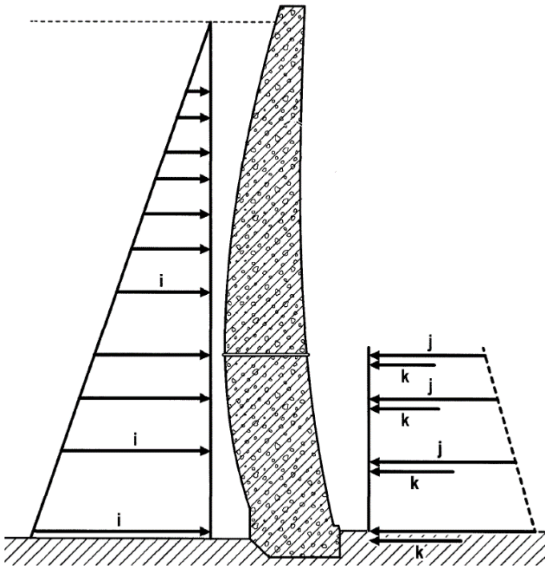


Figure 1 (left). Schematic cut-away drawing illustrating the concept.
Figure 2 (right). Pressure profiles applied on the upstream face (i) and on the downstream face of the existing arch dam (j = pressure in the bladders, k = mean pressure on the face, depending on the bladder's surface).

Moreover, if the hydraulic connection is permanent, then the system operates fully automatically. This also allows for compensation of the potential leaks of the bladders in order to avoid (or limit) pressure drops.

3. From Concept to Detailed Design

Based on this concept, EDF's Hydro Engineering Centre is currently developing a detailed design to reinforce a 57 m high arch dam with a 25 m high downstream structure. The name of the dam is not reported in the paper for confidentiality reasons, the owner awaiting the administration's authorization to carry out the project before communicating further.
The major questions to be solved by the design studies are discussed in the following sections.

3.1. GENERAL LAYOUT AND SIZING OF THE BLADDERS

The bladders could theoretically be made-up with any shape, and be laid out with any geometry, but regarding manufacturing rationalization and installation aspects, the best solution appears to be a layout with vertical strips.

The actual sizes of the bladders are also limited on the one hand by manufacturing and handling issues, and on the other hand by strength reasons.

The most critical aspect of the bladders is their thickness, which is actually the distance between the bearing surfaces of the dam and of its reinforcement structure (see Figure 3.). This distance corresponds to the diameter Ø of the free edges of the bladders, and the tension T in the membrane is directly proportional to it and to the internal water pressure p, according to the well-known formula (1):

$$T = p\text{Ø}/2 \qquad (1)$$

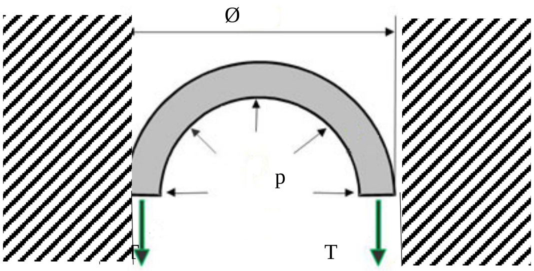


Figure 3. Typical cross section (not to scale) illustrating forces applying on free edges of the bladders.

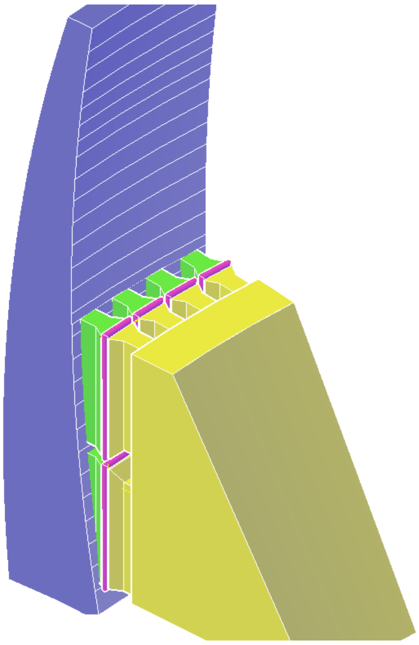
An 80 cm thickness seems to us the minimum acceptable size in order to allow access to the inner space between the bearing surfaces, for exceptional maintenance purposes. Under a 5 bars working pressure (corresponding to the 50 m water height in the reservoir), the tension in the membrane is hence 200 daN/cm.

From our point of view, the most appropriate technology to fabricate the membrane is using rubber coated fabrics. This technology is already used for rubber dams, which are in some aspects quite similar to the bearing bladders. The usual global safety factor for the sizing of rubber dams' membranes is between 8 and 9. This factor takes into account concentration factor, creep, weathering and the chemical aggressiveness of the environment. The adaptation of the partial safety factors to the bladders' actual environment is aiming at this stage at a 5-6 global safety factor in order to maintain a safety factor of 3 at the end of the 20 years design lifetime. Therefore the initial strength of the coated fabric should be 1 000 -1 200 daN/cm for our project. Despite the fact that design tensions in rubber dams are usually lower than this, some references such as Ramspol barrier in the Netherlands prove that this strength is attainable. Indeed the initial strength of Ramspol coated polyamid fabric was ca. 2 000 daN/m [2].

It is also to be noted that the thicker the bladders are, the more space is wasted between them because of their free edges. A given mean pressure and a given thickness involve thus a minimum width of the bladders. In our case the aimed mean pressure goal is 70 % of the upstream pressure, which means the bladders must cover 70 % of the downstream face of the dam (along the height of the reinforcement structure).

In the light of the previous considerations, the following layout has been adopted for the project: 3.3 m wide bladders arranged along a vertical axis, the total height being divided into 2 rows in order to limit the length of the bladders to 11 m. This layout, illustrated by Figures. 4 and 5., allows the transfer onto the downstream reinforcement structure of approximately 50 % of the total hydraulic load applied on the arch.

Figures. 4 and 5 also show that the bladders will bear on the downstream face of the dam through concrete beams (drawn in green). These beams will be built in order to verticalize and offset the bearing surfaces. Indeed the double curvature of the dam, which makes the crest overhang the face, and which is different for each radial cross section, would make the construction of the reinforcement structure and the installation of the bladders much more complicated without these concrete beams. The same provision is also retained for the bearing surfaces onto the reinforcement structure, in order to create vertical access wells between each couple of bladders.



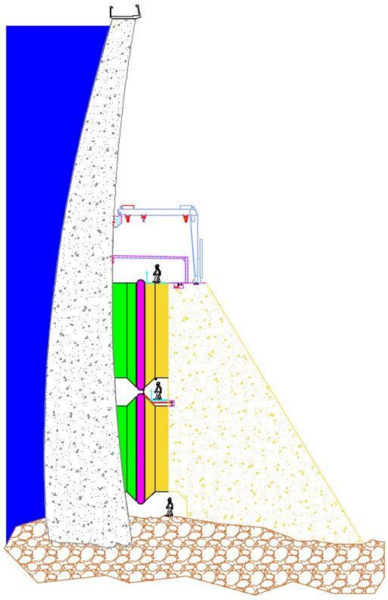


Figure 4 (left). 3D view of the layout of the bladders (drawn in magenta) for one block.
Figure 5 (right). Cross section of the layout of the bladders.

3.2. WATER SUPPLY NETWORK

Pressurizing of each bladder will be ensured by a fitting placed on top of it. Pressurizing only requires that the bladder be connected to the reservoir through one small hose, as demonstrated by Pascal's barrel experiment. The design of the network is in fact based on reliability considerations. The first retained principle is to dispatch the bladders between several independent networks, and to connect adjacent bladders to different networks in order to avoid a total loss of pressure on several blocks in case of failure of one network, as illustrated in Figure. 6.

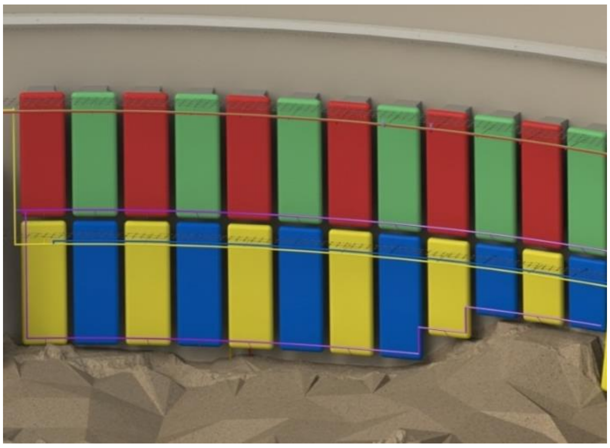


Figure 6. Layout of separate networks (each network has a different color).

Another fitting will be placed at the bottom of each bladder, for initial water filling.

The diameters of the pipes, hoses and fittings, and especially the ratio between them will determine the velocity in the different sections, and so the pressure drops along the hydraulic circuit. The diameters are thus defined by the acceptable losses of transferred loads for a given size of the failure point.

Our analysis leads to a diameter between 100 and 150 mm for the main pipes, 50 mm for the top pressurizing hoses, and 25 mm for the bottom filling fittings.

Depending on the specific environment of the dam, another function of the water supply network must also be to provide water treatment to avoid proliferation of bacteria and/or heating to prevent freezing. To that end, a closed loop water circulation can be achieved inside the bladders by using the bottom fittings.

3.3. Installation

The empty bladders will weigh about 1 ton each. Depending on the road accessibility to both the dam's crest and the crest of the reinforcement structure, the handling of the bladders can require the installation of permanent dedicated lifting tools. For instance, it can be a grappler on the dam's crest and a gantry crane on top of the reinforcement structure. In that case it is important to find a solution to limit the height of the bladders when packed for handling. One solution could be to roll them onto a reel. A low pressure air pre-filling will provide for correct shaping before water filling. Unless a bottom supporting cradle is installed, which seems unnecessary under working conditions, the handling fittings will have to support the weight of water required in order to achieve self-support by friction.

3.4. Vandalism and ageing

One of the factors holding back the development of rubber dams in France is due to its (supposed) sensitivity to vandalism. In the case of inflatable bearing bladders, it is worth noticing that the bladders won't be reachable by passers-by, and can be easily fully protected by building a protection roof. Such a roof can also slow down the ageing of the rubber coating of the bladders by protecting them from UV, thermal and rain exposure.

4. Qualification Tests

Several coated fabric products manufacturers have been contacted and have proposed solutions matching the project's strength and size requirements.

The next step now is to perform tests on full scale prototypes, that should start before the end of 2017. Beyond the questions of strength and water tightness of the bladders, the goal of these full scale tests will be to check some aspects difficult to accomplish on a small scale model. So the testing will require building a vertical dedicated testing bench in order to correctly simulate the behavior of the bladders and to check/adapt/define in particular:

- the handling and installation procedure;
- the filling procedure (how to control the final position of the bladder, to avoid the membrane folding and how to release the air during filling-up?);
- the actual final sizes, which depends on creep, friction/sliding;
- the need for a bottom supporting cradle (will the bladder progressively slide down?);
- the actual initial safety factor (on a smallest scale bladder).

Figure 7. shows the design of the testing bench. The physical bottom access will afford a good similarity to the on-site access conditions. The sidescuttles will afford a visual access to several points of one concrete/bladders' contact surface, that will allow to monitor sliding.

Figure 7. 3D views of the 13 m-high testing bench.

The qualification of the bladders will be completed by laboratory tests, with a special focus on ageing, and creep in particular.

5. CONCLUSIONS

The need for reinforcing existing dams will increase in the next decades because of ageing and increase in safety standards. Several projects involving the reinforcement of arch dams have been completed so far, and it often requires building a bracing structure downstream. The link between the existing dam and the new structure is a key issue and in most of the cases it has been designed as a rigid connection which does not allow adjusting or controlling the transferred loads. The Kölnbrein reinforcement project is, as far as we know, the only reference where adjustable devices have been used.

The new solution presented in this paper, is currently under development at a detailed stage and will enable transferring loads from an existing dam to a new supporting structure by using water-filled bladders. This new concept presents many benefits such as automatic adaptation of the load to the upstream water lever, constant load regardless the differential displacement of the supports, and it does not constrain the normal operation of the existing dam for its implementation (no need for dewatering).

In order to demonstrate the feasibility of this solution, full scale prototypes will be tried on a test bench prior to their installation on an actual dam reinforcement project.

6. REFERENCES

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