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Research on the combination of water and membranes as a structural building material.

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Abstract

The aim of this paper is to investigate the combination of water and membranes for temporary architectural applications.

Water as a construction material, can be useful for three different purposes: first of all, thanks to its thermal mass, it can be used as a medium for cooling down or heating up buildings (Pronk *et al* [6]); secondly water is uncompressible and, in combination with air, can be used as part of a structural element; thirdly the mass of water could work as a sound barrier so it can be used as sound insulation material (Rodrigues and Coutinho [7]).

This paper shows the result of the structural behaviour. There is another paper about sound insulation properties of water. The research in both structural and sound insulation fields was carried out in the laboratories of Technische Universiteit Eindhoven, The Netherlands.

The prototype is a “waterbeam” of 2 m span. Starting from the Tensairity® technology principle (Luchsinger *et al* [8]) developed by Airlight, the purpose of this experiment is to replace the iron struts with a second membrane chamber filled with water. Water works well in compression and air prevents buckling. The result is a rigid structural element made by non-rigid material (water, air, membranes and cables) with a significant reduction of weight and cost of transportation compared to the traditional iron beam but also compared with the Tensairity® system. Different bending tests were carried out. In each test, the two chambers of the beam were filled with air or water to understand the material behaviour.

The comparison between the results shows that water works slightly better than air (stiffness increase of a range of 8-13% in the elements filled with water).

Water application in architecture showed promising results. Further investigation (pure compression tests on columns, multiple layers sound barrier) should be carried out. These results could give architects new design opportunities and solutions concerning temporary buildings and moveable architecture. Moreover the company and building construction industry could develop innovative structural elements and new insulation components.

Key words: membranes, pneumatic beam, Tensairity® system.

1. Introduction

This paper investigates the structural properties of pneumatic structures filled with water.

Water covers 70% of our planet and 65% of human bodies consists of it. It is essential for the life of all kinds of plants, animals and human beings. Contrary, water enters only shyly in the building construction process of architecture (as addition for concrete or as fluid for the heating system).

According to previous studies carried out at our University in Eindhoven, the combination of membrane and water is effective for cooling or heating the inner spaces, improving the inner climate comfort. Pronk, De Haas and Cox [6] proved that multilayer membranes filled with heat-transmitting substance make it possible to heat up or cool down a space by radiation. When a fluid is used, the principle of vacuum-injection can be used to make a heat transmitting membrane with the capacity of 500W/m2*K. The working of the heat-transmitting membrane can be improved by a proper use of the fluid dynamics. Extra membranes could increase the effects because they filter the radiation of the sun and insulate the constructions. Application of this heat-transmitting membrane can be found in the climate control of inflatables, tents and temporary buildings (Pronk *et al* [6]).

In addition, two properties of water have to be highlighted: water is uncompressible and it has a much higher mass than air.

This leads to possible structural applications of water when used as the compressed fluid. The second property drives us to sound insulation applications. If water would have structural and sound insulation properties too, there would be 3 reasons to use it in combination with membranes as a building construction material for architecture.

The results of this research would be highly relevant for architects and construction companies because it could be the starting point for new design solutions and new architectural components too. Moreover, it would be possible to design a rigid structure using non-rigid components only (membranes, cables, water, air). This means a reduction in weight and volume of the construction systems with the consequent reduction of cost of transportation and storage. Mounting and dismantling phases would be simplified too.

This paper investigates water as a structural material. A prototype of a “waterbeam” of 2 m span was built at Buitink Technology, The Netherlands and then tested in the structural laboratory of Eindhoven University. The second part shows the research about sound insulation properties of water. A panel of 150 cm * 125 cm * 20 cm was produced in Buitink Technology and then tested at the Acoustics Laboratory of Eindhoven University.

2. Water as a structural element

Water is uncompressible. Air easily compacts its volume if compressed. For this reason structural inflatable elements filled with air are not so effective except for inflatebles with high pressure or big diameter. Several papers about testing the strength of inflatable fabric tubes or panels have been published. C. Wielgosz, J.C. Thomas, P. Casari [8][9][10] studied the behaviour of high pressure fabric beams and panels. However, the goal of this research is to test the behaviour of a slender and lightweight pneumatic element filled with air at low pressure.

To reach this goal, the combination between air and water should be investigated. Water has a certain mass that does not match with the lightweight requirements; on the other hand water works well in compression. Air, on the contrary, has much smaller mass and it can provide stability at low pressure too. For these reasons a combination of both fluids is required.

Starting from the Tensairity® principle developed by Airlight the idea is to replace the steal struts with a water tube. “The key principle of Tensairity® is to use low pressure air to stabilize compression elements against buckling.

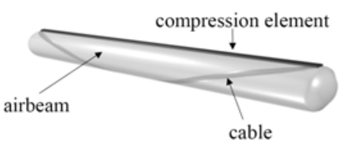

Figure 1

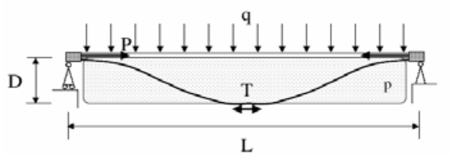

Figure 2

A Tensairity® beam consists of a simple air beam and a compression element which is connected with two cables running in helical form around the air beam (Figure 1, [3]). At the end of the compression element the cables are connected. Due to the connection of the cables with the compression element, the cable force is transferred to the compression element, acting here as a compressive force P” (Luchsinger *et al* [3]) (Figure 2 [4]).

The compression element becomes prone to buckling. In general, the buckling load is much smaller than the yield load meaning an inefficient use of the material and extra weight for the compression element. In Tensairity®, the air tube plays a key role. The compression element is tightly connected with the membrane of the airbeam. Therefore it is continuously supported by the membrane. In fact, the membrane acts as a continuous elastic support for the compression element. The stiffness of this support is determined by the membrane stress, which itself is proportional to the overpressure inside the membrane tube (Luchsinger *et al* [2]). The different cases of a compressed element prone to buckling in truss and in Tensairity® are shown in Figure 3 [4].

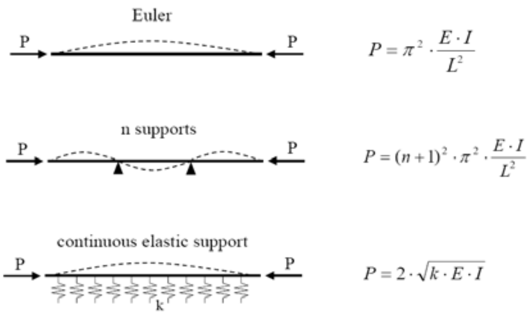

Figure 3

Even though the Tensairity® systems is highly effective, by using the beam this way some of the advantages of pneumatic systems are lost; in fact, the steel girder in the air beam is the weak spot in this high-performance lightweight construction principle. First of all, the maximum length of the steel girder is bounded by the way of transportation and by the length the industry can provide. Even though connections between shorter girders are possible, this means cost and additional work in the construction phase. In contrast, a simple combination of fabrics and fluids (air or water) only has some very attractive features: if it would be possible to substitute the steel girder by an inflatable chamber, the total element can be folded and stored in a simple box. In this way it is possible to transport a construction in a much smaller volume reducing cost and time. Moreover, the set up of inflatable structures is extremely fast and simple and no cranes neither scaffolds are required.

2.1. The mock-up

A mock-up of an inflatable waterbeam was designed and built in collaboration with Buitink Technology. The dimensions of the mock-up are showed in Figure 4 and 5.

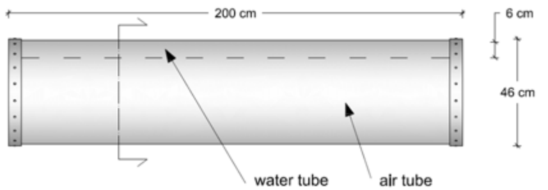

Figure 4

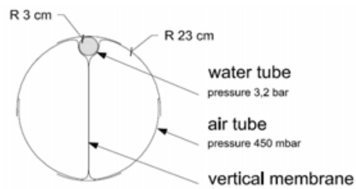

Figure 5

The material used is a pvc coated membrane of a thickness of 1 mm (strain stiffness EA, in warp: 800 kN/m, in weft: 650 kN/m at a stress ratio of 1:1). The waterbeam consists of two chambers filled with different fluids at different pressures. The outer tube is 460 mm in diameter. This tube is filled with air at a pressure of 450 mbar. The inner tube, located in the top part of the big one, is 60 mm in diameter and it is filled with water at a pressure of 3,2 bar. Air pressure level comes from the Tensairity® system that uses low pressure to stabilise the compressed element (Luchsinger *et al* [1]). Water pressure level derives form the pressure of tap water in a common residential building. Both levels of pressure are, therefore, easy to reach with standard devices (air pump, tap water) and are far below safety levels.

Figure 6

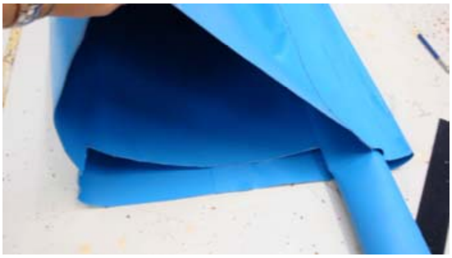

Figure 7

A vertical membrane connects the small chamber with the outer tube. The role of the membrane is to let the two tubes work together and to absorb the shear force. This membrane was designed 20 mm shorter than the diameter of the outer tube, to achieve a good level of tension in it. Joints are two round plates in steel (5 mm thick). The plate has a hole of 60 mm in diameter and a steel pipe of the same size was welded on it. This pipe accommodates the “watertube”.

2.1. Testing

Tests were held in the structural laboratory in TU Eindhoven. The “waterbeam” was loaded by a concentrated force F applied at the mid span of the beam.

Experimental study has been realised for two kinds of boundary conditions. Figure 8 shows the two different cases.

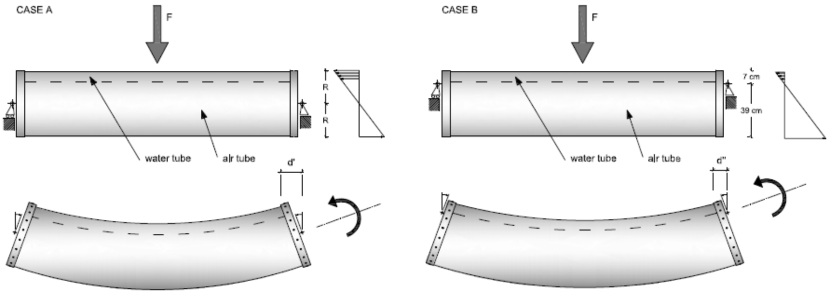

Figure 8

In both cases the beam was constrained by an hinge and a roller. In case A the constrains were placed on the axis of the outer tube. In case B the constrains were moved upwards, close to the compression element. The shifting in the rotation axis influences the stresses in the beam. In Case A, for example, the top part moves internally. The same displacement in case B is much smaller. Case B is the one is used to test Tensairity® technology. Six different experiments were carried out. The aim of the test was to investigate the different behaviour of water an air into the chambers of the waterbeam. The following scheme shows the list of the tests done.

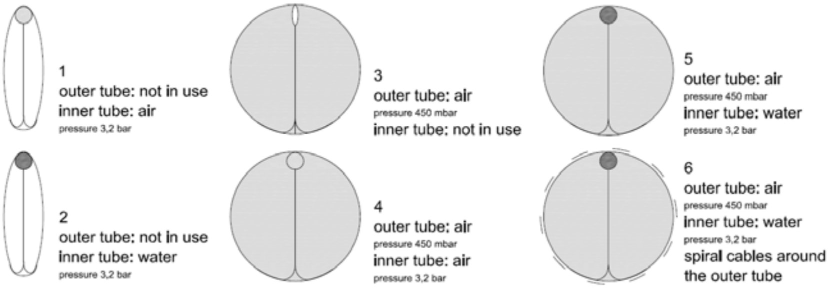

Figure 9

The loading tests stopped when a deformation around 60 mm was reached (Figures 10/11). In case of small deformation and large stiffness of the beam, the force limit was set at 4,5 kN.

2.2. Experimental results

Figures 12 and 13 show the results of two bending test. Chart A is related to the constrains' case A; chart B to constrains' case B.

Figure 10

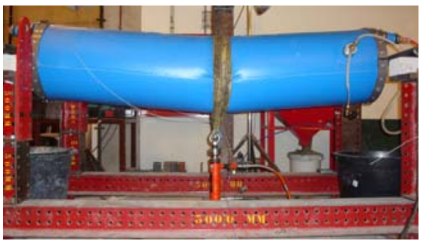

Figure 11

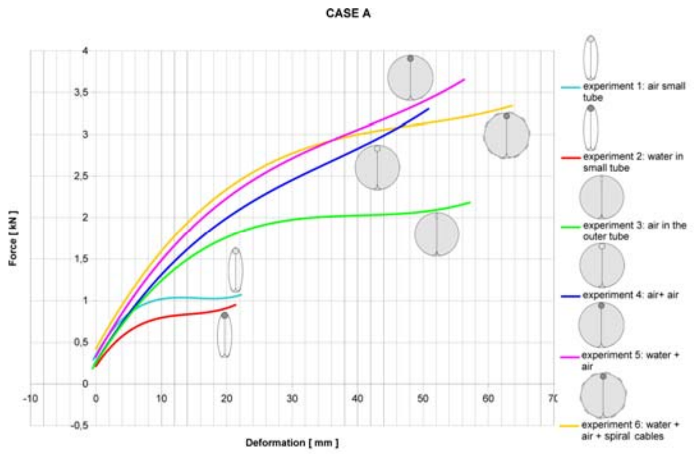

Figure 12

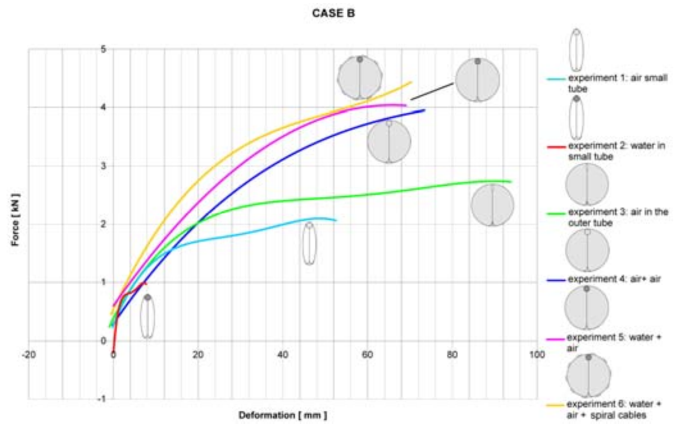

Figure 13

2.3. Discussion

Comparing the behaviour of the beam in the two different cases, the results show clearly that the system restrained with boundary condition B (rotation of the joints at the top) works better than A (rotation in the centre). In case B the beam was stiffer. Spiraled cables gave a little bit of contribution in case B (the result with cables, case A, was even worst). One reason for this small improvement gave by cables could be that the pretensioned internal vertical membrane works efficiently, absorbing the shear force and the tension in the lower fibers. So, spiraled cables seem not to be as fundamental as in the "waterbeam" as they are in the Tensairity® beam.

Curved shapes are similar and the following comparisons and considerations can be done.

Comparing the behaviour of test 1 (inner tube with air) and test 2 (inner tube with water) without the help of the outer tube, air system works 20-30% better. The reason could be that when the outer tube is deflated, the water chamber does not work in compression. In this case, the tube may not behave as a beam but as a yarn. The dead load of water could be relevant, increasing the displacement due to the bending moment. (Figure 14)

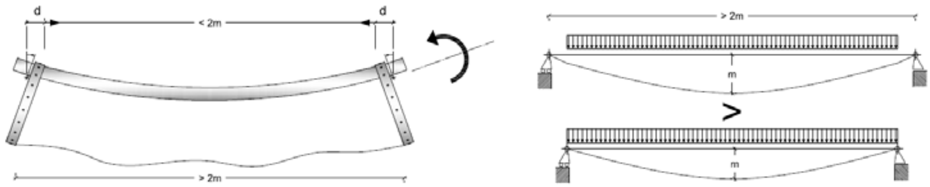

Figure 14

Test 3 (outer tube filled with air, no contribution of the inner chamber) shows the stiffness of an inflatable beam filled at low pressure (450 mbar) is much higher than the stiffness of a small tube filled at high pressure (3,2 bar). This means the stiffness of an air beam may be more influenced by the dimension of the cross section than by its internal pressure.

Comparing test 4 and 5, we can state that water, as fluid for the inner chamber, has a better result. The improvement of the systems is in a range between 8 and 13%. This result proves the hypothesis we have started with that water, like all incompressible fluids, works better than air in compression. (Figure 15).

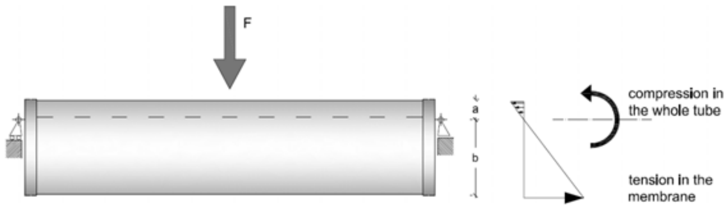

Figure 15

Spiraled cables in test case B contribute to improve the stiffness of the beam. However the vertical membrane seems to works well absorbing the shear force and the tension force in the lower fibers. (Figure 16).

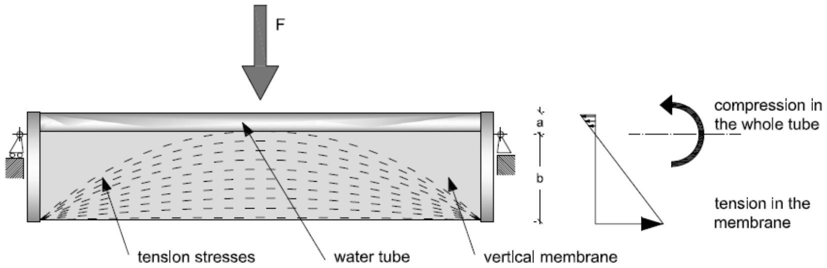

Figure 16

Acknowledgement

Buitink Technology and Structural Laboratory of Eindhoven University played a key role in the success of this research.

4. Conclusions

The research proved that water can be used as structural material for architectural application.

Structural application confirmed that water, as an incompressible fluid, works efficiently in compression and could contribute to the stiffness of a structural element. Advantage of this application is the possibility to have a slender pneumatic beam without any contribution of rigid struts. The structure is, therefore, completely foldable. Disadvantages are the increase of weight of the structure in use and the buckling load, not known yet. Further investigation as, for example, pure compression test is required.

As a conclusion, we can sum up the advantages of using water in architectural applications: firstly, the large (heat) accumulating capacity (please look at the other papers by the same authors); secondly, the capability to resist at compression; thirdly, sound insulation capacity (please look at the other papers by the same authors). In addition we should mention the low price and the availability. These last two points are of great importance because they assure that these kinds of application could be used almost everywhere, as long as water is available in the surroundings.

Systems described before could be used for temporarily structures, such as pavilions, tents, and for exhibitions but also for free-form architecture. In addition, due to the availability of the material, applications in case of emergency are also possible. These kinds of solutions

References

[1] Luchsinger R.H., Crettol R., Steingruber P., Pedretti A. & Pedretti M., 'Going strong: From inflatable structures to Tensairity', in *Textile Composites and Inflatable Structures II*, E. Onate & B. Kröplin (eds), CIMNE, Barcelona, pp. 414-420, 2005.

[2] Luchsinger R.H., Pedretti M. & Reinhard A., 'Pressure induced stability: from pneumatic structures to Tensairity', *Journal of Bionics Engineering*, 1, 141-148, 2004.

[3] Luchsinger R.H., Pedretti A., Steingruber P. and Pedretti M., "Light weight structures with Tensairity", R. Motro (ed.) *Shell and Spacial Structures from Models to Realization;* Editions de l'Espérou, Montpellier, 2004.

[4] Luchsinger R.H., Pedrett, A., Steingruber P. and Pedretti M., The new structural concept Tensairity: Basic Principles, in *Progress in Structural Engineering, Mechanics and Computation*, ed A. Zingoni, A.A. Balkema Publishers, London, pp. 323-328, 2004.

[5] Plagianakos T. S., Teutsch U., Crettol R., Luchsinger R. H., Static response of a spindle-shaped tensairity column to axial compression, in *Engineering Structures*, Volume 31, Issue 8, pp. 1822-1831, 2008.

[6] Pronk A.D.C., de Haas T., Cox M., Heat-Transmitting Membrane, in *International conference on Textile Composites and Inflatable Structures*, Barcelona, 2007.

[7] Rodrigues and Coutinho, Master of Science Thesis *Evaluation of the Sound Insulation of Liquid-Filled Panels*, International conference paper for Internoise, Shanghai, China, 2008

[8] Thomas, J.C., Wielgosz, C., Deflections of highly inflated fabric tubes, in *Thin-Walled Structures* 7 July, 2004

[9] Wielgosz C., Thomas J.C., Casari P., Strength of inflatable fabric beams at high pressure, 43rd AIAA/ASME/ASCE/AHS/ASC Structures, *Structural Dynamics, and Materials*, Denver, 22-25 April 2002,.

[10] Wielgosz C., Thomas JC, Deflections of inflatable fabric panels at high pressure, in *Thin-walled structures*, June 2002