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Design and Analysis of Reinforced Rubber Membranes for Inflatable Dams

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Key words: Inflatable dams, composite materials, stress concentrations, fluid-structure interaction.

Summary: The aim of the present paper is to present actual calculation approaches and design aspects of inflatable dams. The analytical calculation of design relevant stresses in the membrane of inflatable dams is too vague. Therefore, finite element analyses are needed to get the stresses of the multi-ply composite material with cover layers of rubber. Because of the rubber layers the inflatable dams are sometimes called rubber dams. In the end of the actual investigations, there should be a design concept for inflatable dams accordant to the Eurocode-concept. Stress concentration factors, gained of finite element calculations, lead to the relevant stresses. Reduction factors for the different material behaviours are determined independent of numerous calculations.

1 INTRODUCTION

The Federal waterway network in Germany comprises about 7,350 km of inland waterways. There are more than 300 weirs in order to raise water levels and allow navigation. Many of them have reached their lifetime and must be replaced in the near future. Traditionally, these weirs were made of steel. Since several decades a new weir type exists – the inflatable dam. They are considered because they can be more cost effective compared to steel gates [1]. An inflatable dam consists of a multi-ply rubber membrane, filled with air and/or water and clamped to the weir body with one or two fixing bars. For hydraulic reasons breakers can be attached to the dam body, see Figure 1.

Figure 1: Inflatable dam with breakers near Marklendorf at the river Aller

Since 2006, five inflatable dams were commissioned at the German waterways with a height up to 2.5 m, e.g. in Marklendorf at the river Aller. These dams were designed according to the "best practice" principle with a relatively simple design approach. Currently, two water-filled inflatable dams are planned with a dam height up to 5.0 m requiring a detailed design method, which does not exist yet. Only Japan has a technical standard, but it is not according to the Eurocode standard.

The aim of the actual investigations is a design concept for inflatable dams

2 STRUCTURAL DESIGN ASPECT

Water filled inflatable dams are considered for a better control behaviour [2]. Therefore, only the water-inflated dams are considered at the federal waterways. The inflatable dams are basically very similar in their structure. Different manufacturer use their “own” clamping system, e.g. the below introduced and investigated design of the clamping system. This paper deals not with the Pros and Cons of the different designs.

2.1 Geometry and clamping system

The appearance of an inflatable rubber dam depends on geometric, hydraulic and material parameters. The geometric parameters are: the span width l, the distance of the clamping lines b, the height w of the clamping lines, the small height h, the angles β_1 and β_2, the slope of the weir pier and circumference U, see Figure 2. Because of geometric dependences the angels β_1 and β_2 are defined as a function of the other parameters.

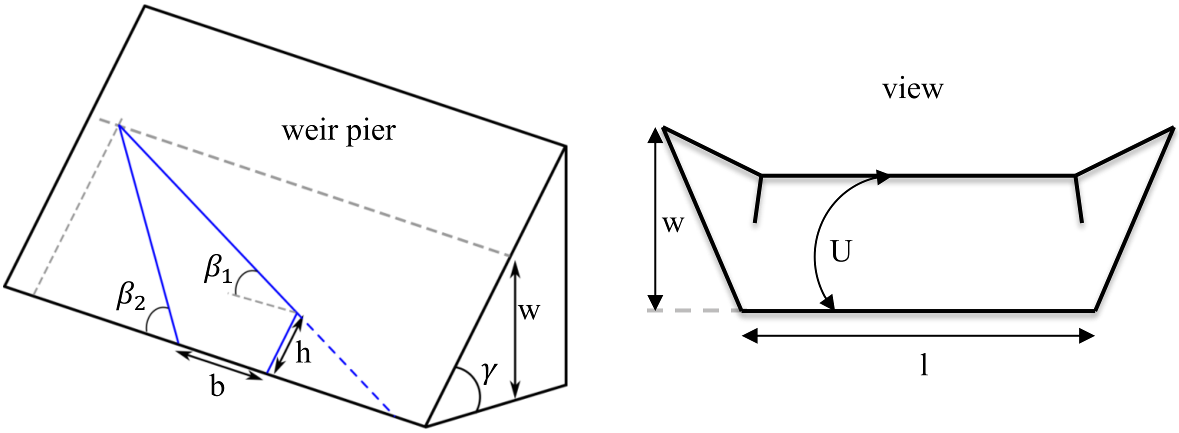
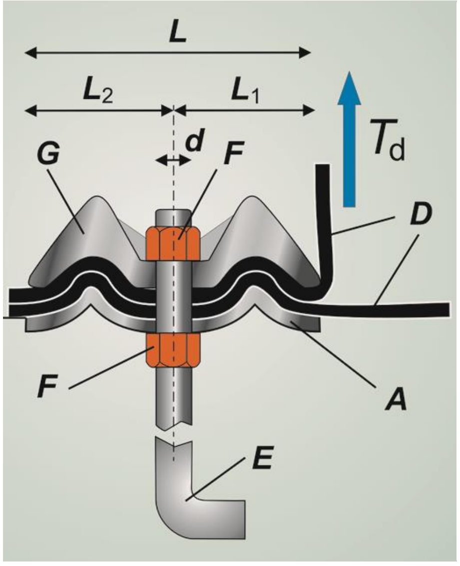


Figure 2: left: Schematic setup of selected clamping geometry (blue lines) on a weir pier; right:

The dam height is substantially determined by the circumference and the distance of the clamping lines. The other parameters matter only for the weir piers and therefore, the stress concentrations of the membrane in the folds near the weir pier. According to circumstances on the construction site, the parameters can depend on the local boundary conditions.

Dependent on suppliers several profiles of fixing bars are used for clamping. A cross section of a possible fixing bar is shown in Figure 3.



Key:
A: lower metal bar
D: membrane
E: anchor bar
F: nut
G: compression plate
L: metal bar witdh
T_d: membrane force
d: diameter of the anchor bar

Figure 3: Fixing bar with anchoring [3]

In comparison to other application areas of membranes, inflatable rubber dams are not prestressed in the classical meaning. The main loads are the pressure inside the tube and the headwater. So the hydraulic parameters are defined as the inside water pressure head h_i, the upstream water level h_o and the downstream water level h_u.

2.2 Material

The material used for inflatable dams is descended from the rubber industry. Manufacturing of a rubber membrane requires large scale rubber vulcanizing equipment, usually an autoclave or heated press machine. There are tension members in between of layers of rubber. The tension member for the construction of inflatable dams what we are looking at is a polyester or polyamide fabric. These fabrics are covered with rubber, in our cases ethylene propylene diene monomer rubber (EPDM) or chloroprene rubber (CR).

One method involves procurement of pre-vulcanized rubberized fabric sheets and bonding these together in a press machine. The continuous product from the conveyor belt production is divided according to the circumference. These strips are placed side by side and joined together by separating the layers of fabric and re-vulcanization of the joints to produce the tubular membrane. On the construction site, the ready-made membrane only needs to be attached to the clamping system on the weir foundation. Conveyor belt products with textile tensile members for weirs have a customized thicker rubber layer which is later on the outside of the inflatable rubber dam. This thicker cover layer is for the protection of the tensile members with respect to abrasion, vandalism and weathering [4].

There is also a disadvantage of this thick layer for bending behaviour. We assume for the fabric only a high tension resistance, but for the rubber a very small one. Instead, there is a strong resistance against compression. Figure 4 shows a tensile specimen under bending load.

Figure 4: Bending characteristics of membranes for inflatable dams

The length of the specimen is 320 mm and has a shape of specimen A of DIN EN ISO 283 [5]. The specimen is about 13.5 mm thick and is executed with two fabric layers. The thicker coating is about 7 mm. The two ends are hold together with adhesive tape, which is on the right in Figure 4. On the left side, a pair of forces arises. Here, the blue arrows symbolise the compression part in the rubber and the red arrows the tension part in the fabrics. Because of this, the tensile stress in the fabrics increases, see below.

The breaking strength of the fabric is tested in own laboratories in warp and weft direction. The stress-strain-behaviour is nearly linear, see Figure 5.

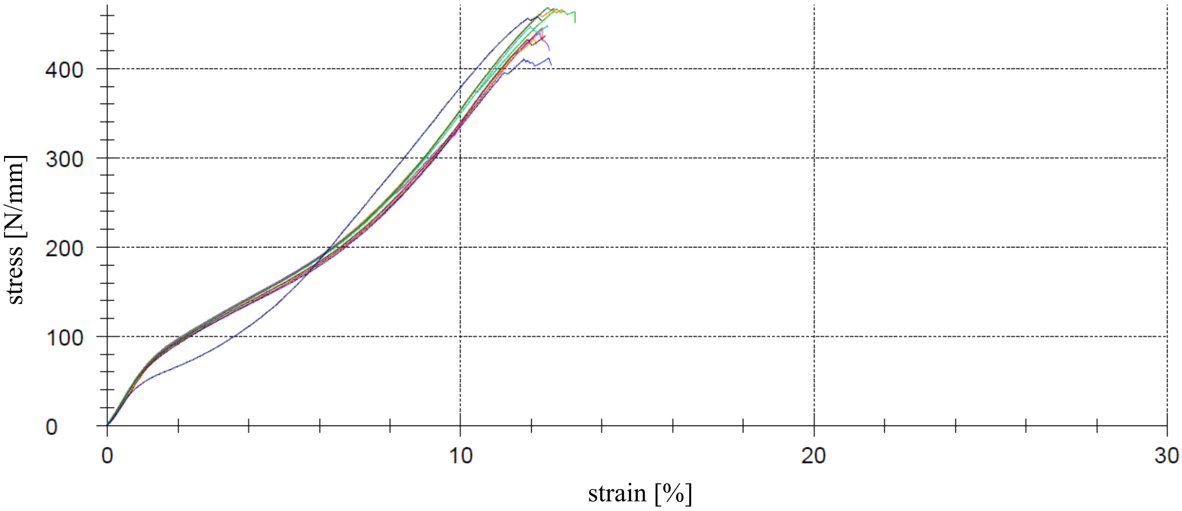


Figure 5: Stress-strain diagram of a two-ply rubber membrane

The first approach in the finite element modelling of this material was a homogenisation of the compound. The bending behaviour of the material is overrated with this assumption, because the tensile stiffness is in the fabric. The Young's Modulus in the software needs the reference to a cross section. Hence, the thickness of the compound material leads to a small Young's Modulus, but also to a great thickness. The thickness is linked with the third power, so that the bending influence induces too high stresses in the calculation. Therefore, the material composition has to be modelled more detailed. The next approximation would be a tripartite cross section with a lower and upper part of rubber and middle section as homogenised fabric(s).

In the first place, the compression part of the stress-strain diagram of the different types of rubber is unknown. It is complicated to get the same boundary conditions in the compression test as in reality. In the axis of compression is an "endless" material with no defined height (Figure 4). At the right angel to this axis there is on the one hand an endless part and on the other hand a free end and an end with fabric as tension member. Therefore, two tests were made – an unconfined and a confined compression test. For the linear parts of the stress-strain diagrams a Young's Modulus between 5 and 3500 N/mm² was obtained.

Three different compression modulus (600, 300 and 30 N/mm²) were tested in bending conditions in an example. A fictive cross section with one single, homogeneous fabric layer exactly in the middle of the 10 mm thick sample was chosen in a finite element simulation. The Young's modulus for the fabric was 1200 N/mm² and for the tension side of the rubber

5 N/mm². For a high resolution of the stresses each rubber layer was calculated with six integration points and the fabric layer with four integration points. Fully integrated shell elements were used. As a consequence bending stresses can be seen in the fabric layer (Figure 6). Here, the yellow coloured part is the blurred fabric and the grey coloured parts are rubber layers. In the upper rubber layer are nearly no stresses, because of the low Young's Modulus of the rubber, in comparison to the stiffness of the fabric layer. With the increasing compression modulus the pressure zone in the lower rubber layer increases. But also the stress in the fabric layer increases. Finally, as expected, the compression modulus influences the stress in the fabric.

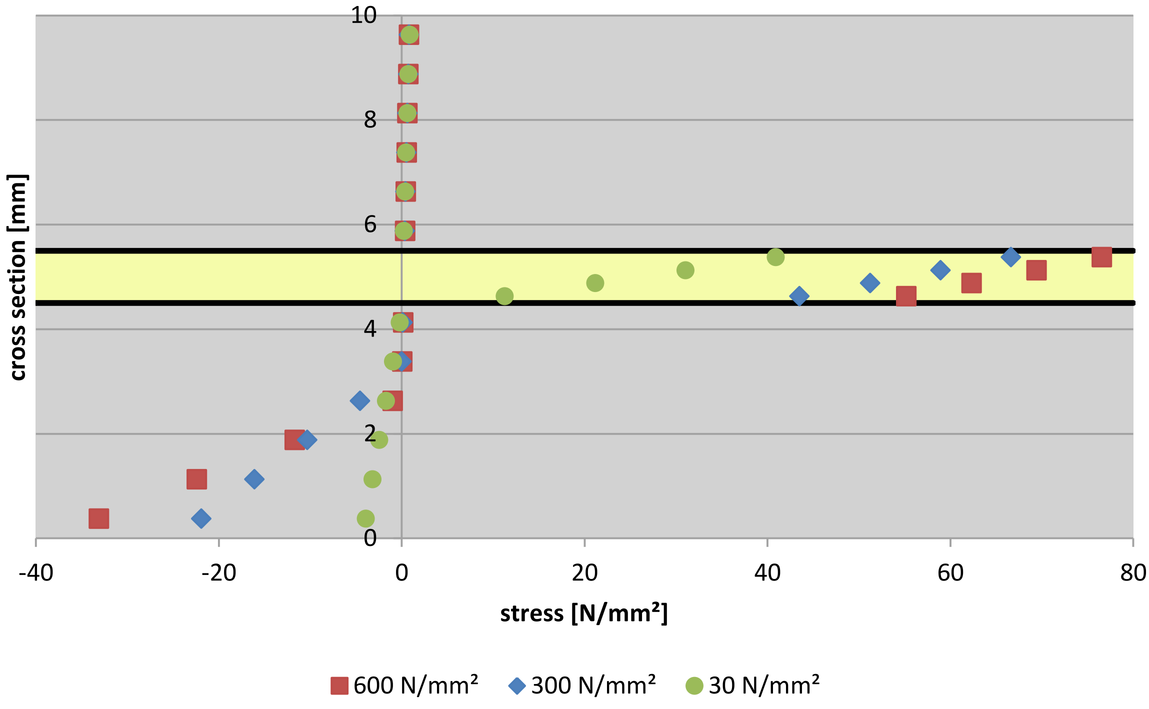


Figure 6: Cross section with different compressive modulus

Here, the fabric layer is modelled with the theory of thin shells. Further investigations will use membrane theory for the fabric.

2.3 Membrane forces

The force T in a cross section of a water-filled type and a design case with full headwater can be calculated analytically [6] with

$$\mathrm{T} = \frac{1}{4}\,(2\alpha - 1)\,\rho_W g\, h_s^2\ . \tag{1}$$

Here α is the internal pressure coefficient, which is in case of water filling the proportion of the inside water pressure head h_i and the upstream water level h_o. Further, ρ_W is the density of water, g the gravitational constant and h_s the dam height. In the undisturbed areas of the cross section the analytically calculated forces correspond with the results of finite element simulations.

Stress concentrations near the clamping lines or in folds near the weir pier cannot be determined with equation (1). For this purpose further finite element simulations are needed.

3 FINITE ELEMENT SIMULATION

All calculations were made with the explicit finite element analysis software LS-Dyna. This software was chosen because of the many material models, contact algorithms and the quasi-static fluid-structure interaction. Here, the fluid is replaced by an energetically equivalent load vector [7,8]. Because of the large number of variables, it is appropriate to use ANSYS Mechanical as part of the pre-processing process.

For symmetry reasons only the half of an inflatable dam has to be modelled. This 3D FE-Model is divided in three chambers: inner volume, headwater volume and downstream volume. Each chamber can be filled with water and/or air. All chambers have to be enclosed, that is why there have to be walls on the downstream (UW) and the upstream (OW) side of the inflatable dam. In Figure 7, the delimiting wall on the downstream side is not shown for a better view. The inner chamber is the inflatable dam itself and is limited by the light-blue, dark-blue and red parts. The upstream chamber is limited by the red, brown and yellow parts. At least, the red, blue and grey parts describe the downstream chamber. The weir sill, made of concrete, is modelled with a rigid material.

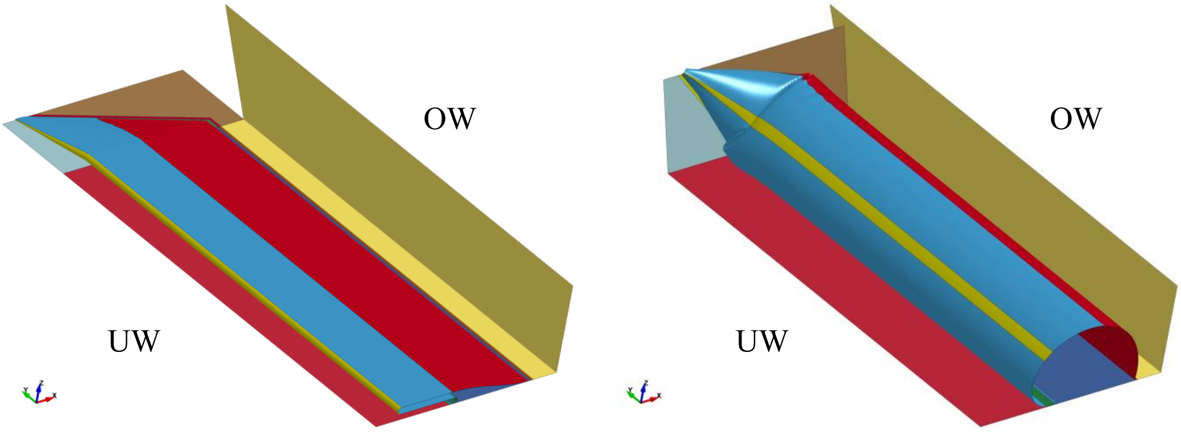


Figure 7: FE-Model, left: deflated dam, right: water inlated dam with headwater

Figure 7 on the left shows a deflated rubber dam while on the right side an inflated dam with headwater is shown.

The aim of this initial state is to get an unstressed condition. Therefore, the parts, which should be stressed, are initialized with the corresponding stresses. In this case the state of stress is similar as if the membrane would be brought from a flat and unstressed membrane in this state. For the same reason the slope of the weir pier is zero at the beginning. The yellow and green stripes in the weir body are “special” parts on which initial stress is initialised. This initialisation allows an unstressed condition, when the membrane lies flat on the ground.

At the start of the simulation the weir pier gets the right slope, while gravitation is already working. After this movement the filling medium is raised slowly, quasi-static. Hence, no unphysical behaviour should occur. In the end, the headwater and/or the UW water level are raised slowly.

The shape of the inflatable dam adjusts itself while the load is applied. Hence, the final dam height is a result of the geometric and hydraulic parameters. For the standard design case the headwater level has to be iterated, whereby the increasing headwater influences the dam height.

Beside the model of the entire dam, smaller models were used for detailed investigations. There are used models only for the undisturbed cross section in the middle of the weir. But in all these models the influence of the clamping system is not considered yet. In this case the stress concentrations in these areas depend on the element size of the finite element mesh.

3.1 Loads

The common design situations for inflatable rubber dams are persistent design situations, like own weight and hydrostatic pressure (inside the tube and on the upstream side) and transient design situations, like hydrostatic pressure from the downstream side, ice load, wind and temperature. The actual investigations are limited to the persistent design situations.

3.2 Stress Concentration Factor

For the design of an inflatable dam, it would be smart, if it is possible to get the relevant stresses by calculating the circumferential stress analytically with equation (1) and multiply it with a stress concentration factor (SCF). There could be a stress concentration factor for the membrane near the fixing bars and others for several folds. The SCF can be calculated with the help of FE-simulations with

$$\mathrm{SCF} = \frac{\sigma_{FE,\ max}}{\sigma_{\mathrm{analytic}}}\ . \tag{2}$$

Here $\sigma_{\mathrm{analytic}}$ is the analytic solution and $\sigma_{FE,\ max}$ is the chosen respecively maximum stress in the inflatable dam. There will be a separate SCF in the fabric directions weft and warp, too. In the end, the stress concentration factors could be used in a design concept, so that no extensive finite element calculations have to be done.

3.3 SCF caused by fixing bars

In the numerical investigations on inflatable dams, the fixing bars were not modelled. In reality the membrane is bended over the fixing bar at the downstream clamping line. Because of that, the geometric boundary condition is missing and the stress concentrations normally influenced by the clamping system depend in these cases on the size of the elements.

To get the right stresses caused by the fixing bar, a detail model is used, see Figure 8. The fixing bar itself is simplified to the important boundaries. These are the curves A and B. Figure 8 shows the contour of a fixing bar, which is modelled with shell elements and a rigid material. Hence, there is no stress in this part, what shows the blue colour. The membrane is modelled with shell elements with membrane theory. A linear material model is used for fabric and rubber. The Young's Modulus of the fabric is 3817 N/mm² and 2.4 N/mm² for the tensile part of the rubber. For the compression part of the rubber a Young's Modulus of 300 N/mm² is freely chosen. The complete membrane has a thickness of 15 mm with a single, homogenised fabric layer of 4.0 mm thickness and an eccentricity of 1.75 mm.

The simulation is initialised with a straight and unstressed membrane. One end of the membrane is fixed under the fixing bar and the other end is pulled around the bar with motion boundary conditions. For an inflatable dam with a height of about 4.5 m, a membrane force of about 120 N/mm (with in total 4.0 mm of fabric lead to 30 N/mm²) is set up. Then, this force pulls at this end, while the motion boundary condition died. The force depends on the height of the weir and can be calculated analytically, see equation (1). Turquoise areas show the applied stress. Here is no stress increase detectable. Only the points A and B show higher stresses, whereby the stress at B is approximately half as great as at A.

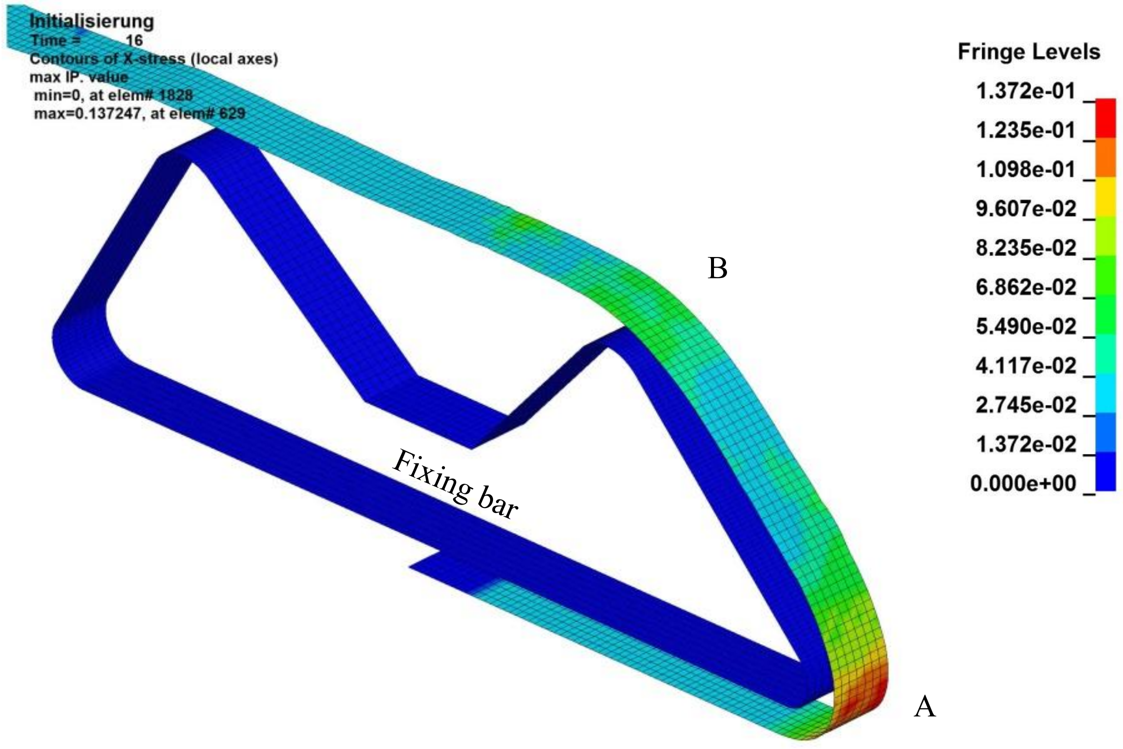


Figure 8: Detail of a membrane stripe bendet bendet over a fixing bar

With this boundary conditions (geometry of the fixing bar, material parameters and membrane load), the stress concentration factor in warp direction for the fixing bars is about 5.0. This means that the stress is five times higher than in the undisturbed circumference. In this case the homogenised fabric layer is eccentric, whereby the thicker rubber coating is in the pressure zone, like in Figure 4. This is the normal installation method. If the membrane would be turned around, the SCF would decrease to 4.2 with this configuration. In the first configuration with a reduced Young's Modulus for compression part of the rubber of 5 N/mm², the SCF decreases to 4.0.

The stress might increase further in the corner between weir sill and sidewall. This is the point where the maximum stress was detected in investigations without modelling the fixing bar. In this case, there will be another, higher stress concentration factor.

3.4 SCF caused by folds

Folds exist in the filled inflatable dam. In this condition is too much material in transverse direction, see Figure 9. This "excess" material is needed in the deflated condition. At this juncture the membrane has to lie down flat on the weir sill during flood events. If it will not lie even on the ground, the membrane could be damaged and consequently the dam will not work anymore [6].

In the state of damming, the folds are unfavourable. On the one hand water can flow through the folds depending on the geometry of the clamping system, what is unwanted, and on the other hand there are stress concentrations in the membrane.

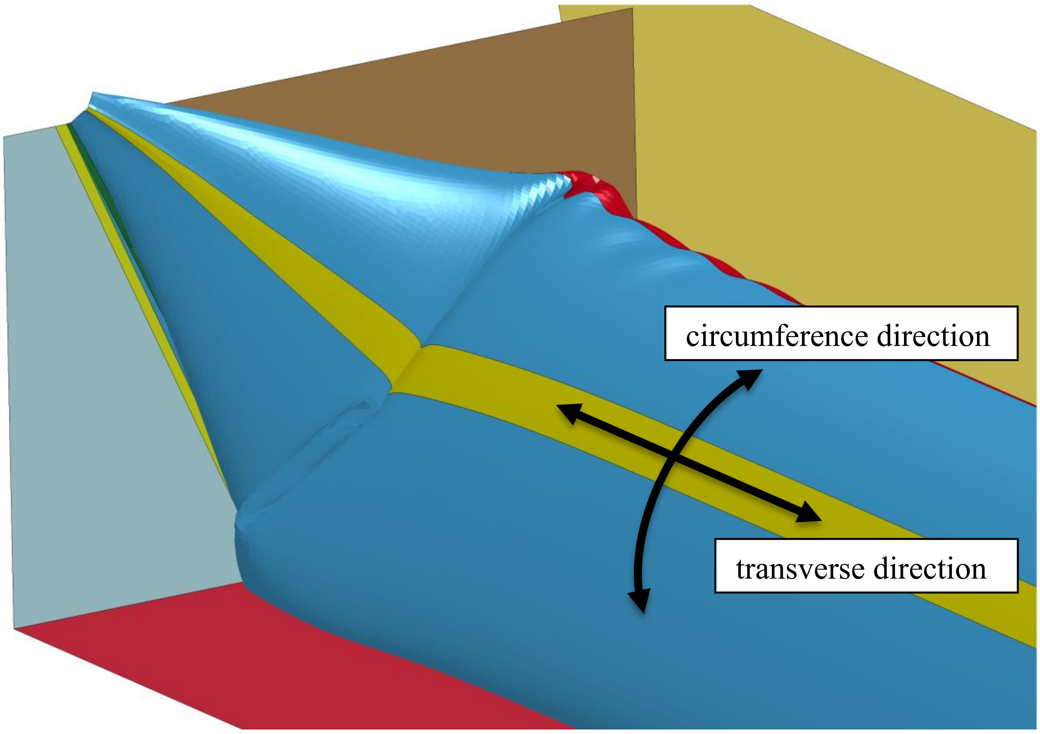


Figure 9: Folds near the sidewall

In FE-simulations nearly no stress is detectable in transverse direction on top of the weir. The folds act like springs. The material in the folds buffers the elongation of in transverse direction. In comparison to the Barlow's formula, the end of the tube is not closed as in the formula assumed. The concrete made weir piers lead the forces into the ground and not back in the dam. Thus it appears that the stress concentrations in the folds are a result of the bending characteristics of the compound material as it can be seen at the fixing bars.

4 REDUCTION COEFFICIENTS

Like in other applications for the fabrics in membrane structures made of polyester or other synthetic polymers, the material is subjected to effects on ageing, creeping, a loss of strength and others. In contrast to solar panels the tension members are protected by thick cover layers of elastomers. Hence, the properties for the elastic materials have to satisfy high requirements. Impacts on the fabric materials are lower than in common membrane constructions like roofs of stadiums or solar panels. An additional benefit of the inflatable weirs is the water cooling of the material as a result of the water inside the weir. As a consequence, the influence of temperature is considered to be less important. An effect which is more important for inflatable dams is the delamination. Repeated bending could lead to a delamination of the rubber layers from the fabrics. This effect is proven with the de Mattia testing according ISO 132 [9]. Hence, no reduction coefficient is needed for this effect.

At two inflatable dams of the Federal waterway network in Germany unstressed material samples are installed under water and air condition in 2009 and 2006 for ageing investigations. In 2015, parts of these samples were used for tensile tests. The mean value of 20 tests with the 9 year old material in warp direction is about 95 % from the starting value. With a minimum value of 87 % and a maximum value of 100 % the reduction of the breaking strength is still within a good range. The remaining part of the sample is reinstalled at the weir site for further investigations. At least one membrane for inflatable dams should work for 30 years.

5 CONCLUSION

The actual investigations show a good approach for the calculation of inflatable dams in combination with investigations of the material behaviour. Analytically calculated stresses can be confirmed using the Finite Element Method. With a sufficiently accurate material law and construction material tensions in wrinkle areas can be determined with sufficient accuracy in further steps. The accurate determination of the characteristic values is part of further investigations. Stress concentration factors should be established to determine the design relevant stresses based on the given boundary conditions. Using the design concept, which is to be created during the current research project of BAW, allows the proof of the stability of an inflatable dam.

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