# INFLATABLE GATES – STRUCTURAL DESIGN OF RUBBER GATES

by

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## 1. INTRODUCTION

As inflatable gates were used more frequently in Japan, a design standard was introduced. This Japanese standard has been updated several times since its first introduction and has been a guide line for the design of all inflatable gates in Japan and the majority of dams worldwide. This design standard forms a connection between the boundary conditions and functional requirements the gate must fulfil and the structural design of the gate. It is more complicated to lay a connection between the required reliability according to the Eurocode and the design, since there is no Eurocode regarding inflatable gates and the Japanese standard gives no values for this. In some projects efforts have been made to follow a Eurocode approach and this information is shown in the report. Important building stones in the design for a rubber gate are boundary conditions and design constraints, the design approach of the rubber fabric, the clamping system, and the hydraulic design in case of overflow.

## 2. BOUNDARY CONDITIONS AND DESIGN CONSTRAINTS

The most important design constraint for each rubber gate is to prevent vibrations for a prolonged time. Vibrations may lead to abrasion, and abrasion may lead to failure. To do so it is recommended to place a rubber gate perpendicular to the flow direction. If this is not possible (Fig. 1) investigations are required to ensure stability. Also in case of a significant overflow measures need to be taken and investigations need to be conducted to make sure no vibrations occur (hydraulic design). A prolonged time can be as much as several months or even weeks so maintenance and pre commissioning situations may be relevant

Important boundary conditions include:

a. Upstream water levels including extremes, possible limited by situations where a gate is deflated.
b. Downstream water levels including the water level during maintenance conditions.
c. Discharge over the rubber gate, possible partly deflated (see Fig. 1).

**Figure 1: Situation with non-perpendicular flow and (limited) overflow**

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Other boundary conditions that can influence the design include temperature, (wind induced) waves, extreme conditions for UV and ozone, salinity, sedimentation (sand and rocks, see Fig. 2), tidal waves, earthquakes, wind, flow conditions, floating debris, passing ships, ice. The Japanese standard gives directions to calculate with some of these conditions. The properties of the materials used will be relevant. These properties can be influenced by the manufacturer.

**Figure 2: An air-inflated rubber gate with sediment (courtesy of Dyrhoff Ltd.)**

## 3. DESIGN APPROACH RUBBER SHEET

### 3.1 Approach according to JICE (2000)

The basic rule in the design approach for a rubber gate is to calculate the tension in a normal 2D-cross section of the rubber gate, taking into account all relevant conditions, and take an overall safety factor of $F_S = 8$, This overall safety factor is in fact not the right term that describes the structural capacity of a system beyond the expected loads or actual loads. It is defined as the ratio of the (short term) strength of the membrane and the membrane force T calculated in a 2D-cross section.

This overall safety factor $F_S$ is actually the product of three partial factors:

$$F_S = f_1 \cdot f_2 \cdot \gamma = 2.53 \cdot 1.73 \cdot 1.75 = 7.66 \qquad (1)$$

Here, the partial factor $f_1 = 2.53$ is based on strength reduction in creep tests and corresponds to a time period of 30 years (Fig. 3). Partial factor $f_2 = 1.73$ is based on strength reduction in aging tests and corresponds to a time period of 30 years.

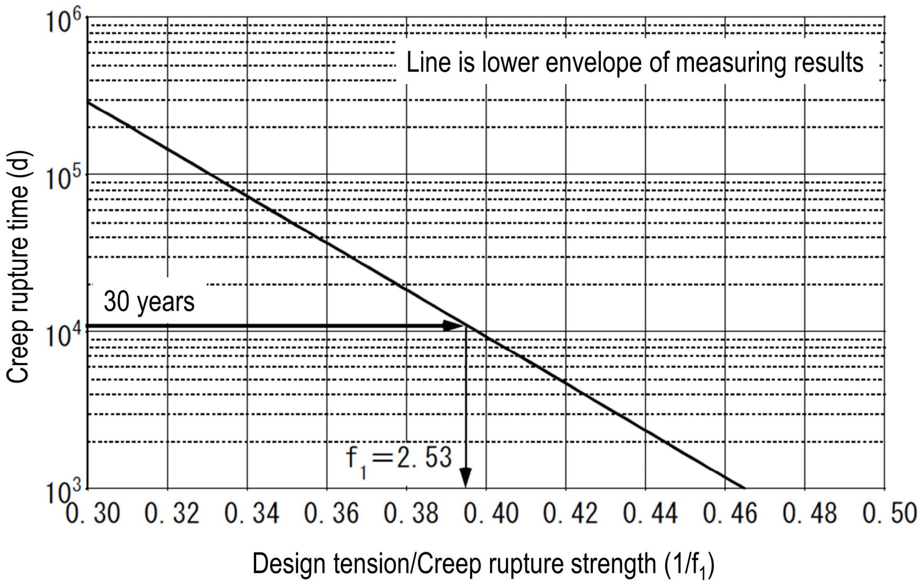


**Figure 4: Result of creep tests on rubber fabric according to JICE (2000)**

Finally, partial factor *γ = 1.75* is a form factor and takes stress concentration into account. Stress concentration is the effect that local stresses can be higher than the average stress as calculated in the middle section. Stress concentrations can occur at or near the abutments. Stress concentration factor (SCF) is mentioned occasionally. This SCF is the ratio between the maximum stress (locally) and the average stress in the middle section. These SCF's can only be calculated with FEM models.

For the strength in warp direction of the gate (perpendicular to flow direction) 2/3 of the strength in a normal 2D-cross section (circumferential direction) is taken.

This design approach is applicable if the basic assumptions of the Japanese standard are met: nylon or a comparable material, life span of 30 years, 3D design with a stress concentration of maximum 1,75, limited overflow (and no vibrations). Deviations of the standard are possible, but it needs to be proven that the solution is safe.

### 3.2 Eurocode and Recommendations of WG166

There is no Eurocode standard for inflatable gates. The working group makes some recommendations how to deal with this situation for the design of inflatable gates in Europe. In these recommendations the design approach depends on the consequence of failure and the degree of proven technology.

- Approach I can be taken when the design of the gate is a proven concept and the height is limited to 5 meter. In this case the Japanese standards possibly combined with European material testing procedures given adequate certainty for the design.

- Approach II is proposed when the rubber gate is not based on proven technology (different materials, new clamping system and/or unproven geometry) and failure has noticeable consequences. In this case the relevant safety factor of 8 needs to be verified by conducting tests to prove comparable effects of aging, creep, abrasion and extreme temperatures. The safety factor needs to be verified by determining the stress concentration Factor. If the stress concentration factor differs from the safety factor used in the Japanese standard, the safety factor should be changed accordingly. The applicability of the clamping system needs to be verified by tests that take into account the effect of relaxation, aging of the rubberized fabric, possible displacements and/or rotations of the anchoring system, possible dynamic loading (short term cycles and long term cycles), possible angles of the rubber membrane in both directions and if applicable possible stress concentrations in the rubberized fabric.

- Approach III is proposed when a rubber gate is a vital part of the infrastructure and failure has serious consequences or when the risk of casualties is significant. This approach is closer in accordance with the Eurocode. The approach has been described in the report including a project application in Ramspol, an 8 meter high storm surge barrier; clearly fitting to the description of "vital part of the infrastructure". For Ramspol scale model test, FEM calculations (Fig. 5), clamp tests (Fig. 6) and rubber fabric tests have been conducted, also taking into account the effects of aging, creep and fatigue.

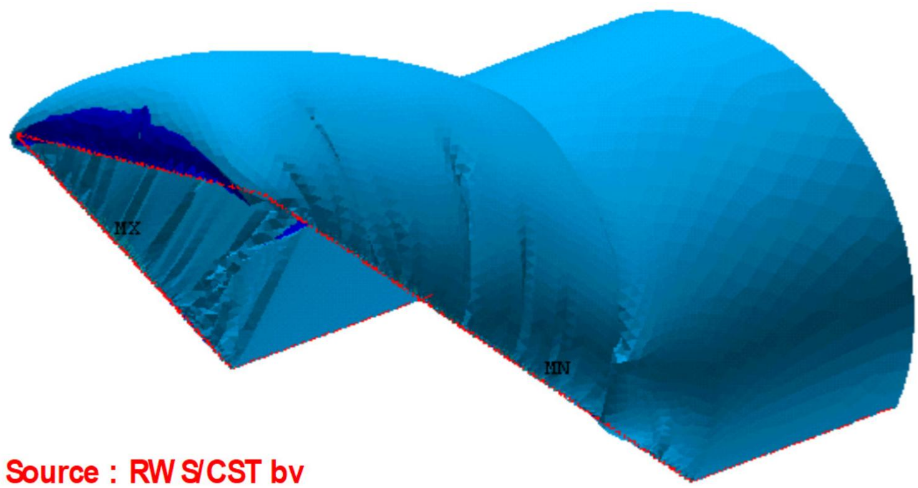


**Figure 5: Results of a 3D-FEM-calculation of a rubber gate**

**Figure 6: Testing of a rubber sheet in the clamping system**

# 4. CLAMPING SYSTEM

The clamping system is an essential part of the design of a rubber gate. In general, the rubber fabric is clamped between an upper plate and a bottom plate with a certain amount of pretension. The shape of the upper and bottom plate can differ for different sizes of the rubber gate and between different suppliers. The design and calculation of the clamping system itself (the steel parts) follow from national design codes for steel structures. The applicability of the clamping system in combination with the rubber fabric is more specific and cannot be found in most national design codes. The Japanese standard (JICE, 2000) prescribes a safety factor 2 between the working load of the bolts of the clamping system and the yield strength of the bolts.

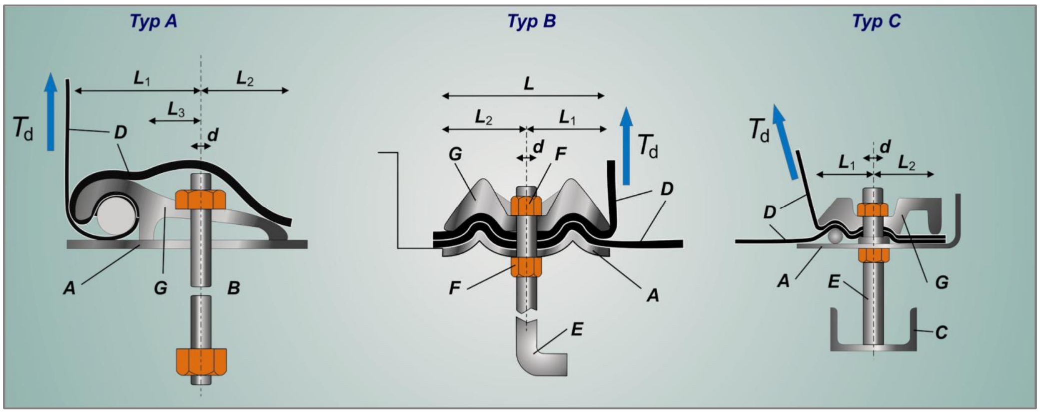


**Figure 7: Examples of clamping systems (Gabrys, 2007)**

In the past 40 years there have been many kinds of clamping systems. Figure 7 shows several examples. The M-type clamp is most common for new projects. To test the applicability of the clamping system the behavior of the rubber fabric in the clamp needs to be tested with regards to aging and degradation, creep and fatigue. There is no general guideline for this kind of test. It is up to the manufacturer to prove the applicability of the clamping system and set the requirements for this. It is a recommendation to allow for sufficient testing and analyses if significant changes in the clamping concept are proposed

# 5. HYDRAULIC DESIGN

## 5.1 General aspects

The hydraulic design of inflatable gates is relevant for several reasons:

- to determine a reliable discharge function in case of overflow;
- to ensure a stable rubber gate with no vibrations;
- to determine an appropriate bottom protection at the downstream side of the gate.

There is a big difference between a water-filled gate and an air-filled gate with respect to the hydraulic design. A specific phenomenon that only occurs with air-filled gates is the V-notch effect. The V-notch occurs due to the density differences of air and water. As membranes are very thin two-dimensional load-bearing structures with relatively low bending stiffness, the system will become unstable if the inner pressure is relatively low in combination with overflow; the membrane will be folded or dented. The resulting V-shaped "dent" will cause the rubber gate to be loaded on one side only and the downstream riverbed to be subjected to locally higher loads (Fig 8). A V-notch makes flow rate adjustment difficult and produces a large flow rate per unit width

**Figure 8: V-notch with an air-filled rubber gate**

## 5.2 Discharge coefficients

In many cases a discharge function of inflatable gates is required for water management and water level control. Much research (Fig. 9) has been done to determine the discharge function of inflatable gates, especially in Japan and Germany. In the report of WG166 insight is given regarding the different formulas that are being used around the world and the coefficients that belong to these formulas (see Fig. 9).

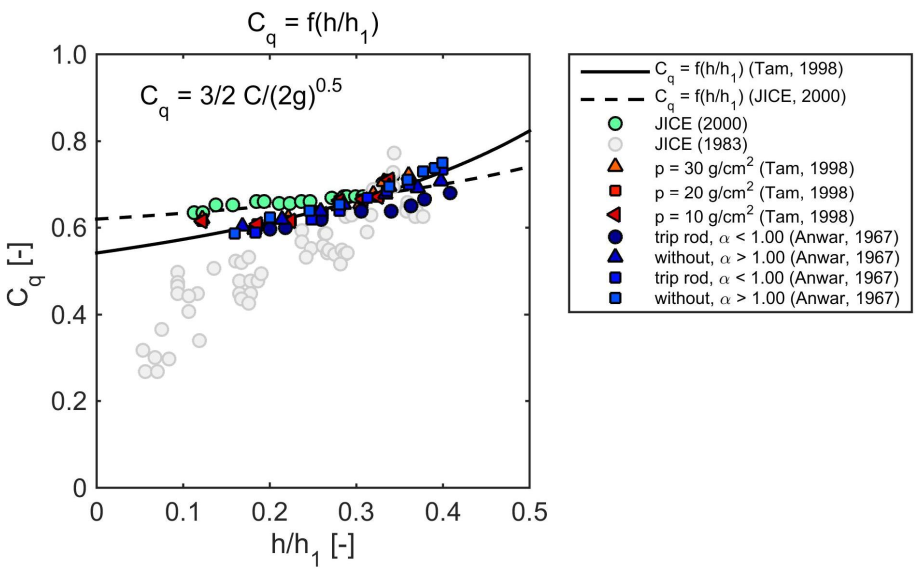


**Figure 9: Comparison of discharge coefficients $C_q = f(h/h_1)$ for air-filled rubber gates**

In Germany additional research (see Fig. 10) has been done to determine the discharge function of a design with breakers. These breakers are introduced to allow a higher overflow over rubber gates without vibrations, and influence the discharge function.

**Figure 10: Scale model of a rubber gate with breakers**

### 5.3 Prevent vibrations in situations with overflow

In Japan the majority of rubber gates are installed for irrigation purposes. Here, JICE (2000) recommends that the overflow depth shouldn´t exceed more than the following values:

1. Air-filled type: 0.2 H
2. Water-filled type:

| | |
|---|---|
| Tailwater has no effects | 0.5 H |
| High tailwater level | 0.4 H (P/H = 2.5 ~ 3.0) |
| | 0.3 H (P/H = 2.0 ~ 2.5) |
| | 0.2 H (P/H = 1.5 ~ 2.0) |

With: H [m] gate height

P [m] internal pressure head on weir sill

Furthermore, JICE (2000) recommends that if the expected maximum overflow depth exceeds the above-mentioned values, effective measures should be taken into account and the effect should be verified.

In the 1970s, Bridgestone developed an air-inflated rubber gate which consists actually of two membranes which were connected at the downstream end. The rubber body laid flat on the foundation when deflated in order to avoid abrasion. When inflated, a fin was formed due to the connection of the upper and lower membrane providing nappe separation and preventing vibrations of the gate (Fig. 11).

Around 2005 the BAW in Germany developed a design with breakers allowing an even higher overflow and tail water level without vibrations. The breakers are vulcanized to the rubber body. Comparable systems of breakers are offered by many manufacturers and suppliers. But there is little knowledge on the effectiveness.

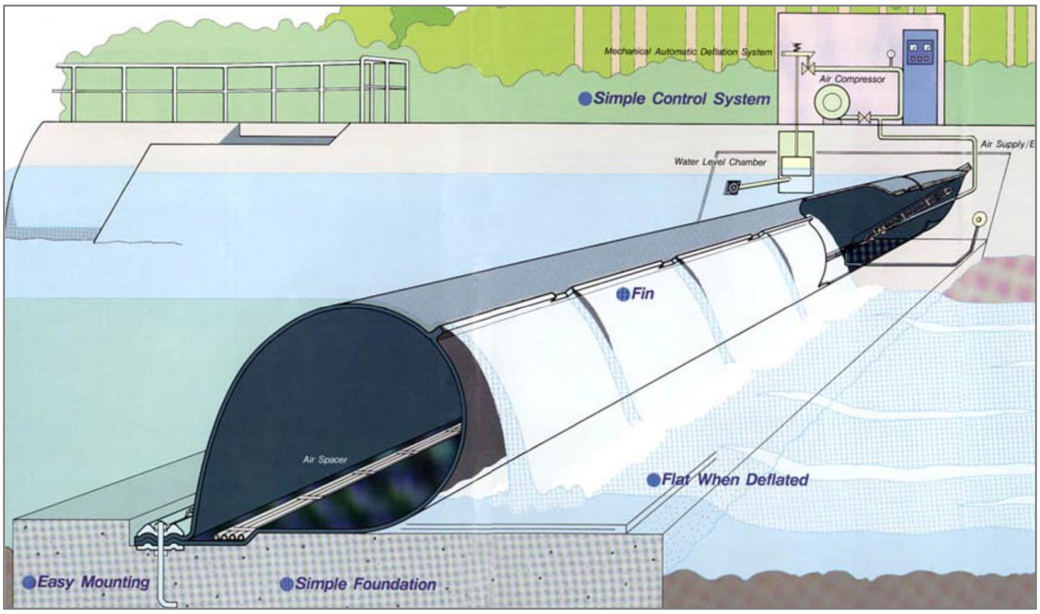


**Figure 11: Cross section of an air-filled rubber gate (fin-type) introduced by Bridgestone (courtesy of Bridgestone Corporation)**

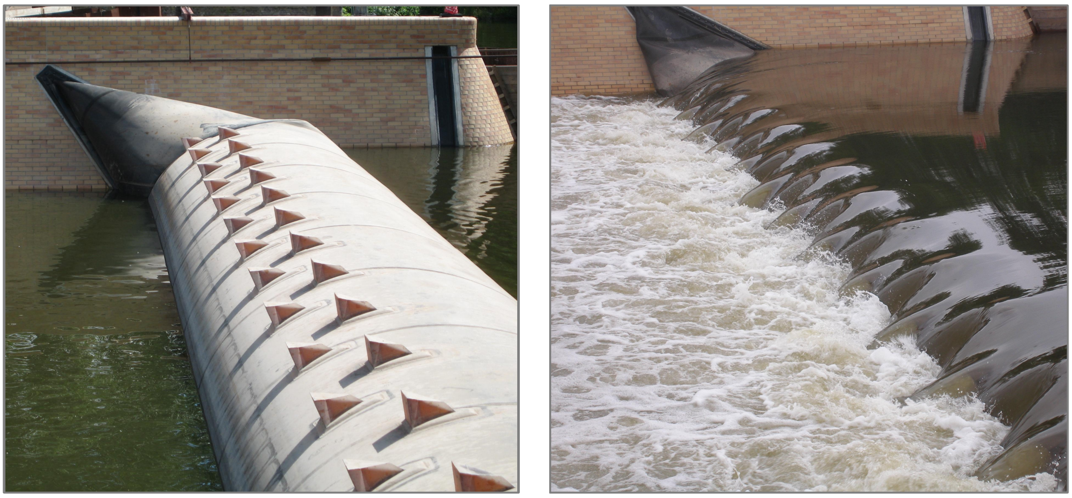

**Figure 12: Water-filled rubber gate with breakers in Bahnitz, Germany**

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