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Indonesian Journal of Science & Technology

Journal homepage: http://ejournal.upi.edu/index.php/ijost/

IJoST Indonesian Journal of Science & Technology

# Prediction of the remaining service lifetime of inflatable rubber dam with deep hole damage

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## ABSTRACT

This paper exhibits a method to predict the remaining service lifetime of inflatable rubber dam by considering the appearance of deep hole damage. The material used for the rubber dam is a composite comprising three layers of woven fabric as fiber and EPDM/SBR 64 474 rubber as a matrix. The service lifetime is predicted by calculating the degradation of rubber dam's material properties. Simple Rate Law model and Time-Temperature Superposition model are employed to calculate the rubber properties degradation. A finite element analysis is then conducted to investigate stress and strain distributions which occur in the rubber dam membrane during operational loading. Furthermore, the effect of deep hole damage in the rubber dam, which is caused by improper maintenance, is modeled as well. The results show that a 7 mm depth of the hole can accelerate rubber degradation, which causes catastrophic failure. This can happen because two layers of the woven fabric in the rubber dam have been broken. Suggestion to hold up the degradation is also discussed.



## ARTICLE INFO

*Article History:*
*Submitted/Received 01 Nov 2019*
*First revised 13 Mar 2020*
*Accepted 27 May 2020*
*First available online 30 May 2020*
*Publication date 01 Dec 2020*

*Keywords:*
*Inflatable rubber dam;*
*Service lifetime;*
*Failure analysi;*
*Composite;*
*Hyperelastic.*

## 1. INTRODUCTION

Inflatable rubber dams are cylindrical rubber fabrics placed across water streams such as river or dam crest, which are used to control the water level by controlling the pressure and volume, hence inflating or deflating (Zhang *et al.*, 2002). The rubber dam is usually bolted into a concrete foundation. They are used to divert water for irrigation (Saleh & Mondal, 2001), temporarily raising existing dams, flood control (Tam, 1997), water retention for aquifer recharge, reducing or preventing saltwater intrusion into freshwater areas, protect low-lying coastal areas from tidal flooding, enabling fish passage past diversion works, by deflation, and for sewage retention/separation during flood events. The membrane is made of rubber, which is reinforced by multi-layer woven fabric material (Gurt, 2015) . The fabric not only has to be flexible but also employs good wear-resistance characteristics. A layer of stainless-steel mesh or ceramic chips is usually embedded in the outer layer to prevent damage due to sharp objects.

Inflatable rubber dams can be filled with water, air, or both. However, more recent development suggests increased use of air-filled rubber because it can be deflated or inflated faster, and they are little affected by freezing conditions during the winter season. Air-filled rubber dam height will be higher than water-inflated at the same internal pressure, which means that an air-filled rubber dam could hold a larger quantity of water. However, the air-filled dam will receive higher tension, which could reduce the overall lifetime of the rubber dam (Alhamati *et al.*, 2005). Characteristic dimensions cover various lengths depending on the needs, while specially-made membranes could stretch up to 200 m wide and 10 m high. Zhang *et al.* (2002) report that a rubber dam can do service for more than 30 years if there is no sharp object knock to the membrane. This can occur when preventive and corrective maintenances are applied periodically. There are several possibilities for damage potential to the rubber dam. Rubber dam prone to damage by a sharp object. The harp object may come from debris after a rainstorm, sharp domestic waste, or construction material (Tam & Zhang, 1999). The rubber usually degrades due to several combination processes that must be checked during maintenance, such as crack growth, chemical deterioration, and thermal aging (Gent, 2001). Analysis of the effect of internal pressure and external water height on the shapes of the inflatable dam was conducted to ensure the safety of the inflatable dam (Watson *et al.*, 1999). However, most of them only deal with neutral water and non-corrosive liquids. In particular case, the rubber dam is employed to store excess acidic liquid waste and prevent it from leaking into the environment while waiting for the treatment. Unpredicted membrane leak must be avoided because it can cause the acid water flood to the environment or natural river. To ensure that the highest safety standard is hold, it is imperative to estimate the remaining service lifetime of the rubber.

In this work, the prediction of the remaining service lifetime of inflatable rubber dam under a corrosive environment is conducted. The inflatable rubber dam in the Tongoloka district, Indonesia, is selected as a case study. This rubber dam has unique operational parameters wherein a one-year timespan; there is a one-month period where the rubber dam is exposed to acidic water. Meanwhile, the rubber dam remains dry for the remaining 11 months. No maintenance of the rubber dam for more than 12 years of operation. Thus, membrane degradation might occur more rapidly.

In predicting remaining service lifetime, an inspection of the current rubber membrane material is conducted with various characterization methods combined with theoretical predictions and compared with data found in the literature. The rubber dam membrane comprises of three layers of woven fabric material as reinforced fiber and rubber as the matrix. Tensile tests for each constituent material are conducted to obtain the current tensile properties. These properties are then compared to the original tensile properties to obtain the degradation curve of the material. A numerical model is then developed to investigate stress distribution along the membrane. Furthermore, the effect of deep hole damage to stress distribution and failure of the rubber dam is discussed.

## 2. INFLATABLE RUBBER DAM SPECIFICATION

The rubber dam used in Tongoloka has been in operation for 12 years. Although it is only used to increase a dam capacity for one month of each year, the degradation of membrane properties due to environmental conditions such as temperature, humidity, and acidic fluid exposure, as well as lack of maintenance process might lead to membrane failure. In the 12 years period of operation, corrective maintenance has been done only once at the ten years mark. The maintenance includes membrane patching to fill hole damages and paint to add an extra layer of UV protection. The patch material used in the corrective maintenance is EP 100 Polyester Fabric 1.8 x 500 x 10,000 mm, with a CN bonding layer on both sides. **Figure 1** shows the general characteristics of the inflatable rubber dam installed in Tongoloka. The inflatable rubber dam consists of EPDM/SBR 64 474 rubber as matrix and woven fabric as reinforcement. The original material properties of the rubber are shown in **Table 1**.

**Table 1**.Rubber properties of inflatable rubber dam

| No | Properties | Value |
|---|---|---|
| **1** | Tensile Strength | 20.2 MPa |
| **2** | Elongation on Break | 430% |
| **3** | Density g/ccm (inf.), 23°C | 1.110 g/ccm |

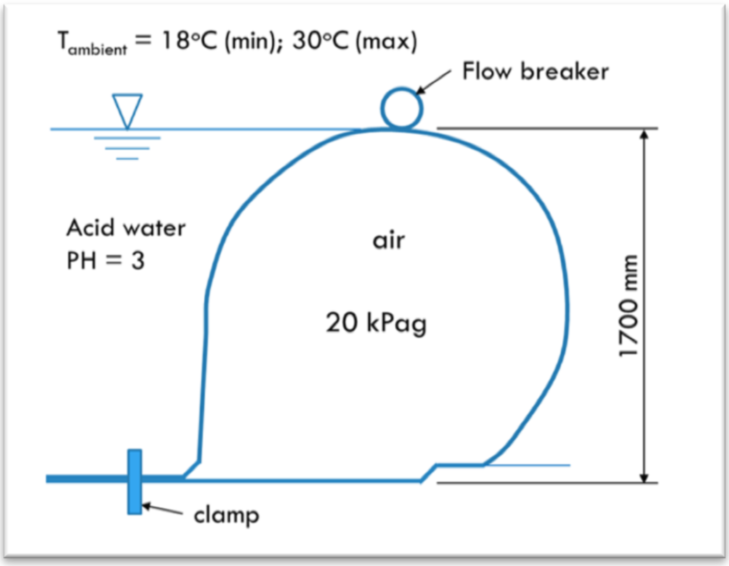


**Figure 1**.Tongoloka rubber dam characteristic.

## 3. MATERIAL CHARACTERIZATION

Material characterization was performed to measure the current condition of the rubber dam. The information on the current material condition is critical to predicting the remaining lifetime of the rubber. In this case, two characterizations were conducted: (1) tensile test and (2) laser microscope observation. The specimens for the characterization were taken from the unloaded part but still exposed to the acidic fluid in the inflatable rubber dam body.

To investigate the degradation of tensile properties, a tensile test was conducted for three material configurations: rubber only, woven fibers only, and rubber-woven fiber composite. The standards used as the reference for the tensile test are ASTM D412, ASTM D885, and ASTM D3039 for the rubber, the woven fabric, and the rubber-woven fabric composite respectively. The specimens after testing are shown in **Figure 2**. Stress-strain curves for rubber, woven fibers, and the composite membrane are presented in **Figures 3**, **4**, and **5**, respectively.

By comparing the results shown in **Figures 3 and 4**, it is clearly seen that fiber is much stronger and stiffer than rubber. This is obvious since the fiber is primary used to hold tensile loading in the composite membrane. In contrast, the fiber naturally cannot hold compressive loading. Such loading is usually held by the rubber. In **Figure 5**, the stress-strain curve of the composite membrane with one layer of woven fiber shows a combination of rubber properties and woven fiber properties. An interesting observation also occurs from the composite specimen, as shown in **Figure 2c**. The interfacial damage, together with rubber failure, dominantly occurs when a tensile load is applied to the specimen with a 45° of fiber direction, indicating the fiber is much stronger than rubber and interface strength.

A Shimadzu Nano Search Microscope SFT-4500 is used to observe fiber structure and measure its diameter. Using the microscope, microstructure and defects in the rubber dam can be observed. The observation can reveal the physical degradation of used rubber. This information is then used to predict the remaining lifetime of the rubber. The result of the observation is shown in **Figure 6**. It can be seen that the observed diameter of one bunch of fiber is around 500 μm (see **Figure 6a**). There is also no indication that the rubber has defects, which may appear due to ozone attack. From **Figures 6b** and **6c**, the averaged fiber diameter of 20 μm is observed.


**Figure 2**. Specimen after tensile tests for (a) base rubber material (b) reinforcement material and (c) composite material.

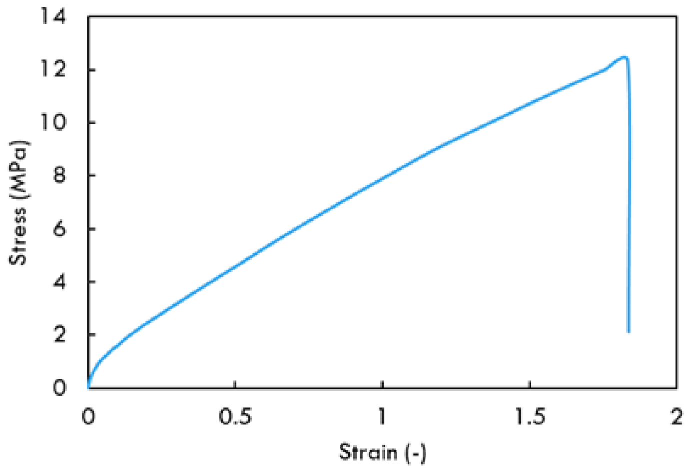


**Figure 3**. Tensile test result of base rubber material.

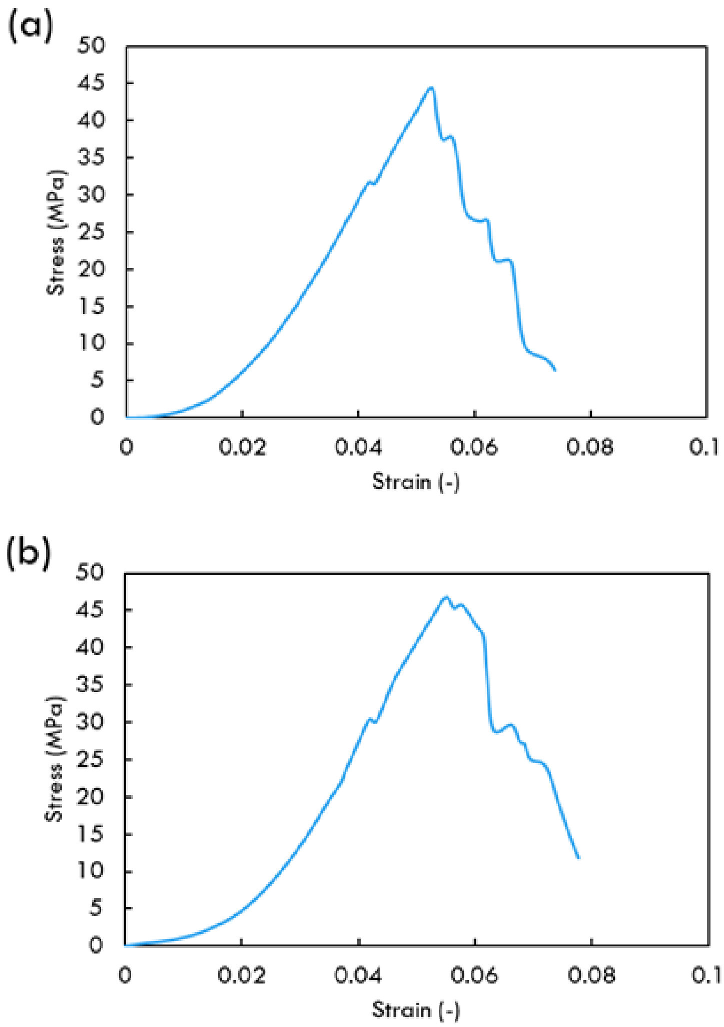


**Figure 4**. Tensile test result of fiber reinforcement material under warp (a) and weft (b) directions.

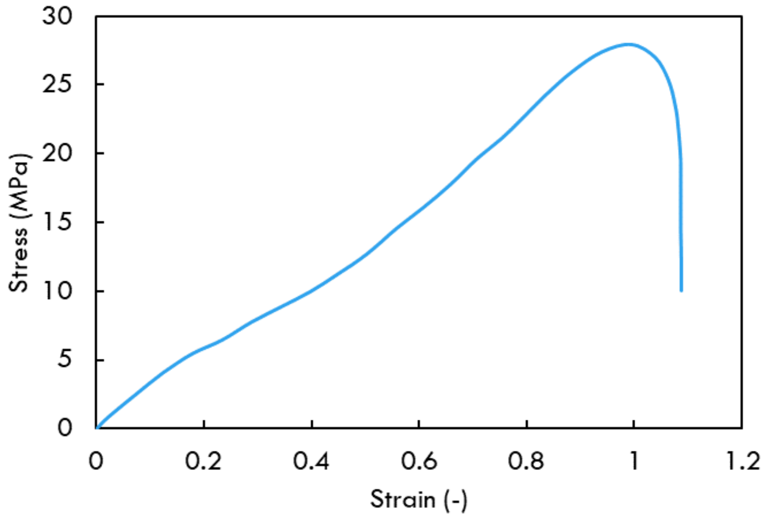


**Figure 5.** Tensile test result of composite 45°.

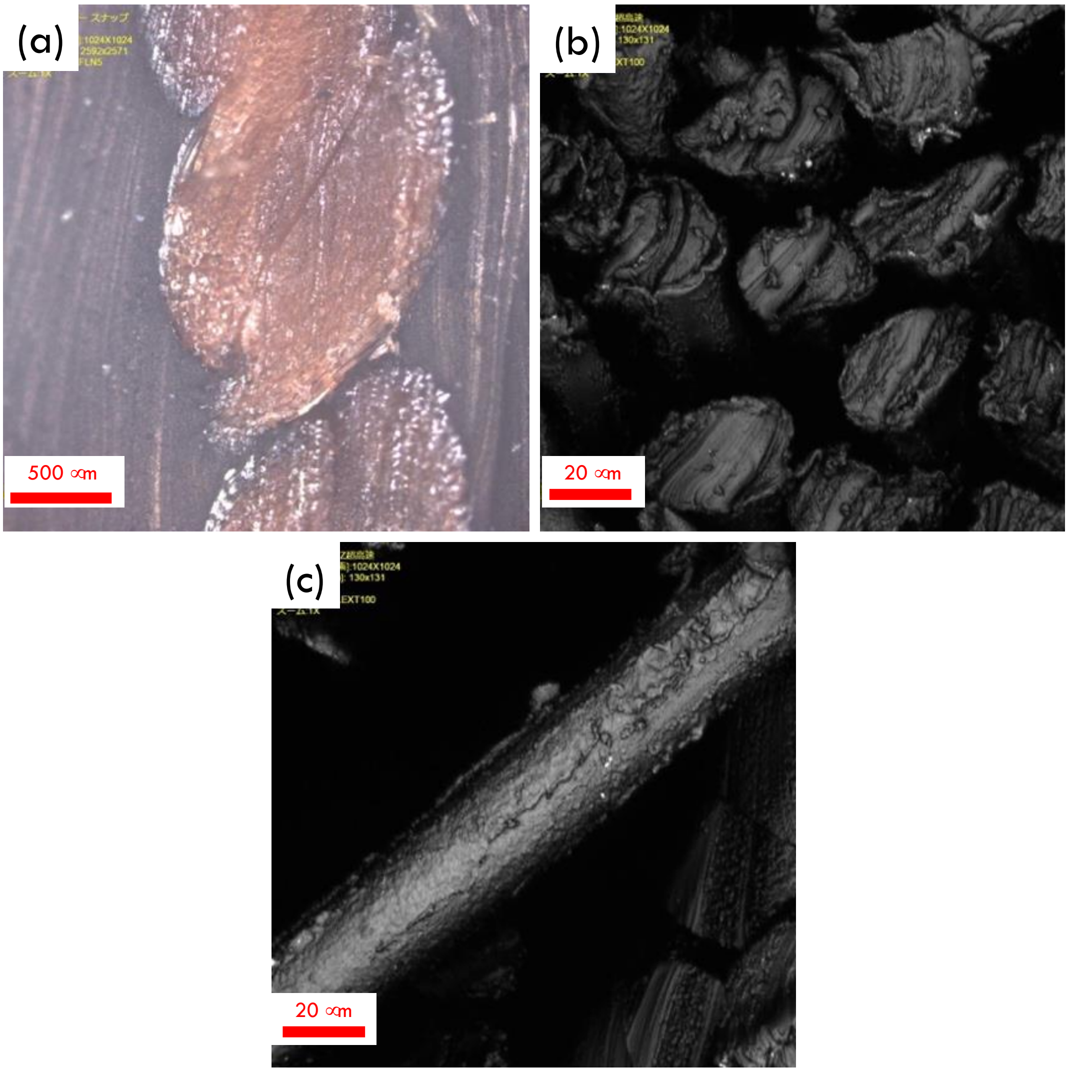


**Figure 6.** Observation result of (a) composite membrane and (b, c) its fibers.

## 4. LIFE-TIME PREDICTION FOR INFLATABLE RUBBER DAM

### 4.1. Models for the life-time prediction

Based on original properties provided by the manufacturer and tensile test results conducted, the degradation of rubber properties can be estimated by using two approaches, namely, Simple Rate Law (SRL) model and Time-Temperature Superposition (TTS) model (Gillen *et al.*, 2000). SRL model uses a second-order kinetics equation to predict the degradation of tensile strength and elongation at break of the rubber as follows,

$$\frac{1}{\zeta_1} = kt + \frac{1}{\zeta_0} \qquad (1)$$

Where ζ1 is the rubber property at any given time (tensile strength in MPa or elongation at break in %), ζ0 is the property at initial condition (tensile strength in MPa or elongation at break in %), k is degradation constant, and t is ageing time (hours). The correlation factor (r2) of the SRL approach for natural rubber aged at 70-110oC is between 0.88 and 0.98.

To minimize the data analysis, a master equation known as TTS model was developed by Gillen *et al.* (2000) as follows:

$$\zeta = \beta e^{-(\varphi . a_T . t)} \qquad (2)$$

$$a_T = \exp\frac{E_a}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right) \qquad (3)$$

where $\zeta$ is the rubber property (tensile strength in MPa or elongation at break in %), $\beta$ and $\varphi$ are the degradation constants, $t$ is the aging time (hours), $a_T$ is the shift factor if the degradation constants are obtained in different temperatures, $Ea$ is the activation energy (kJ/mol) that is obtained experimentally, $R$ is the gas constant (with value of 8.314 x $10^{-3}$ kJ/mol.K), $T_{ref}$ is the referenced temperature where degradation constants are obtained (K), and $T$ is the operational temperature (K).

**Table 2** shows all parameters required for estimating the rubber degradation based on SRL and TTS models. Results of the estimation are then plotted in **Figures 7a** and **7b** for tensile strength and elongation at break, respectively. For both tensile strength and elongation at break properties, the TTS model predicts more degradation of the rubber than SRL model after 10 year operation.

**Table 2**. Degradation Parameters

| No | Parameter | Original | 10-Year Operation (2019) | % Reduction |
|---|---|---|---|---|
| 1 | Tensile strength (MPa) | 20.2 | 13.34 | 34% |
| 2 | Elongation at break (%) | 430 | 206.88 | 52% |
| | **Material Degradation Constants** | | | |
| No | Parameter Name | Symbol | Value for UTS | Value for elongation at break |
| 1a | TTS model degradation constant | $\beta$ | 20.2 | 430 |
| 1b | | $\varphi$ | 4.74 x $10^{-6}$ | 8.4 x $10^{-6}$ |
| 1c | TTS model shift factor | $a_T$ | 1 | 1 |
| 2 | SRL model degradation constant | $k$ | 2.91 x $10^{-7}$ | 2.9 x $10^{-8}$ |

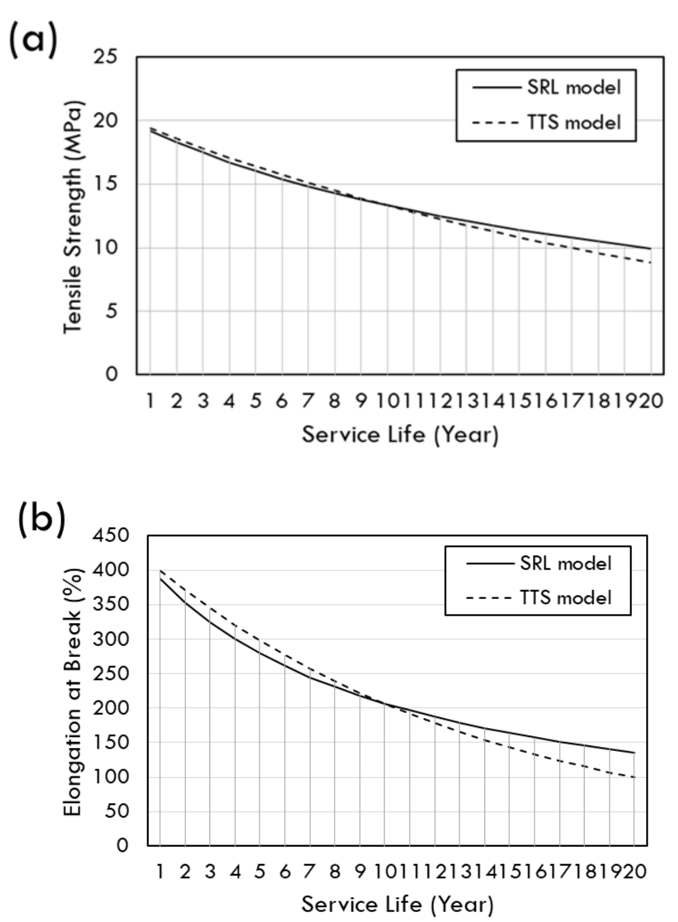


**Figure 7**. The rubber property Degradation: (a) tensile strength and (b) elongation at break.

### 4.2. Whole body model simulation

Numerical simulation is conducted to predict the maximum stress and elongation of the rubber dam for the given operational parameters. Three operation states are modeled: deflated condition, inflated condition with no water load (Idle), and inflated condition with full water load (Peak Load). Two-dimensional simplification is used for the analysis by assuming no significant difference for the stress-strain figure in a longitudinal direction. The material model is assumed to be elastic orthotropic. The result of the analysis is shown in **Figure 8**.

In **Figure 8a**, the deflated condition can generate stress with a maximum stress value of 0.81 MPa. Even though it is considered small comparing with the membrane strength, the maximum stress must be given attention since it can still damage the membrane, especially when the stress is combined by UV light, which may increase the degradation of the membrane. Furthermore, based on the numerical simulation shown in **Figure 8b**, the maximum stress of the rubber occurs during the idle condition in which the internal pressure of 10 kPa causes maximum stress of 3.32 MPa around the clamping point. An interesting simulation result is found at the peak load state (see **Figure 8c**). The presence of hydrostatic pressure can decrease the maximum stress in the rubber dam up to 2.4 MPa in the identic region. This is the characteristic of rubber dam structure by using one-sided clamping in which the inflatable rubber dam is expected to bear hydrostatic load year-round.

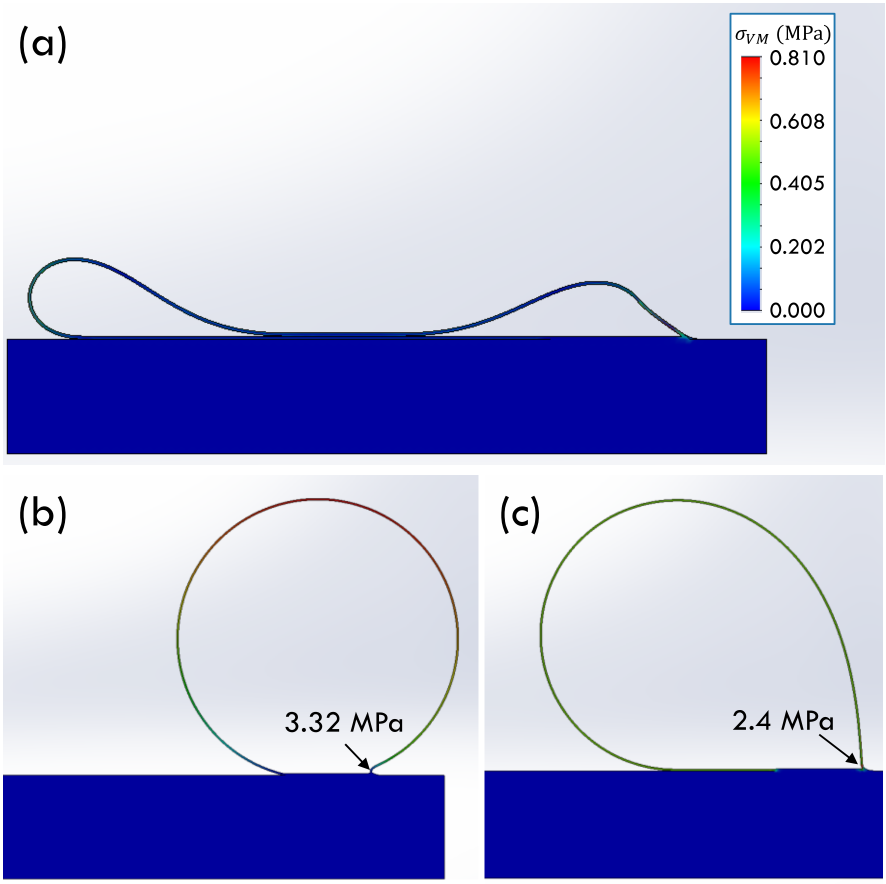


**Figure 8**. membrane simulation results for deflated condition (a), inflated condition (Idle) (b), and inflated condition (Peak Load) (c).

The maximum strain occurs at the peak operational load at 13.5%, which is 6% of the current maximum elongation of the rubber (206.88%). A rubber design guideline provided by Gent (2001) recommends that the operational strain should be kept lower than 15% of maximum elongation and less 10% of its maximum elongation for the rubber to be less prone to ozone crack. Given by the design guideline, the maximum strain is still acceptable at the moment. For a prolonged period of operation, following the trend of SRL and TTS models, the rubber will be significantly less tolerant to ozone crack in 6 years since the maximum strain will exceed the 10% limit. On the other hand, the rubber material might reach its 15% strain design limit in 10 years.

### 4.3. Effect of Deep hole damage in the rubber dam body

Numerical simulation by using finite element analysis is conducted to investigate the stress concentration in the rubber dam due to hole damage. This analysis, which is commonly used in the mechanical analysis, is found to be the most convenient way to predict the stress concentration (Nurprasetio *et al.*, 2017). **Figure 9** shows the rubber dam model geometry used for simulation. The model consists of three layers of woven fabric and four layers of rubber. Four scenarios are examined, which are the model without a hole and the model with a hole of 4, 7, and 10 mm depths. These depths are selected to consider the damage zero, one, and two layers of the woven fabric. The hole damage is positioned in the center of the model. The thickness values of rubber and woven fabric are

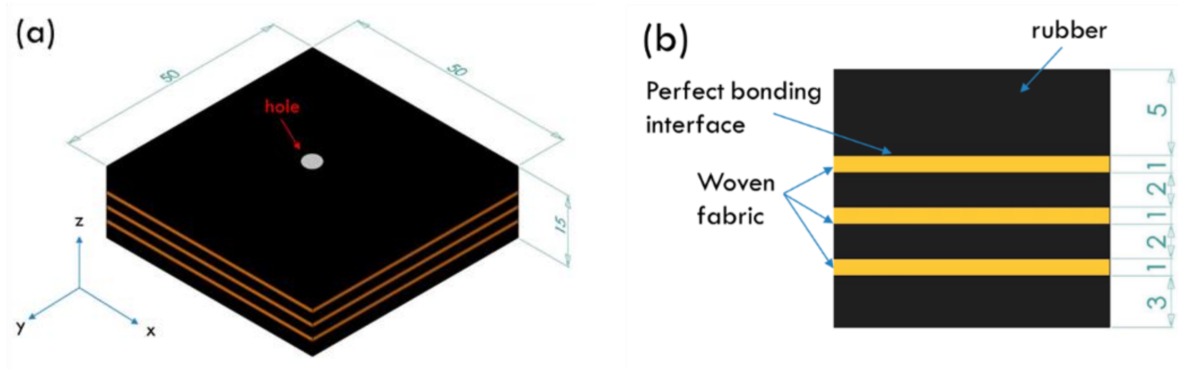


**Figure 9**. Geometry of rubber dam model (a) and layer construction inside the rubber dam (b).

from the measurement of the actual rubber dam. To obtain an accurate result which represents the actual condition of the membrane, the model uses a relatively small size of finite elements (Budiman *et al.*, 2018). Thus, the number of elements used in the simulation is considerably high, especially near hole damages.

**Figure 10** shows the boundary condition and loadings imposed on the model. A uniform pressure of 20 kPa, which represents the air pressure of the rubber dam is applied. Sliding and fixed boundaries are applied at the corners of the model by considering the actual condition in the rubber dam. The uniform displacements of 2.5 mm are applied in *x* and *y* directions. In the simulation, mechanical properties of the woven fabric and the rubber are obtained from stress-strain curves, as shown in **Figure 3** and **Figure 4**.

Furthermore, the interface between rubber and the woven fabric has perfect bonding, which means there is no relative slip nor damage that might occur at the interface.

**Figure 11a** and **Figure 11b** show Von-Mises stress and displacement distributions, respectively. The loads generated by pressure and displacement are mostly bear by woven fabric, which always occurs in composites with a strong fiber-matrix interface (Budiman *et al.*, 2016; Budiman *et al.*, 2017). The displacement distribution also shows a uniform pattern as expected. **Figure 12** and **Figure 13** show stress distribution in rubber layers and woven fabric layers, respectively. Depending on the layer position, the stress distribution might be different. Maximum von Mises stress in the rubber is only 0.68 MPa, whereas maximum von Mises stress in the woven fabric is 19.7 MPa or 29 times higher. From the Figures, the stress variation of both rubber and woven fabric is also considered small.

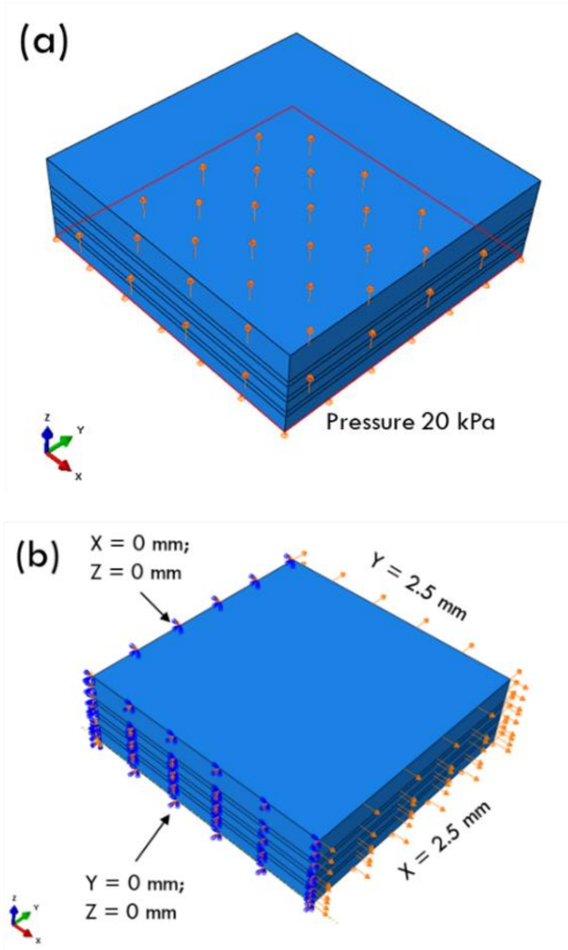


**Figure 10**. Pressurized load (a) and boundary conditions (b) of the rubber dam model.

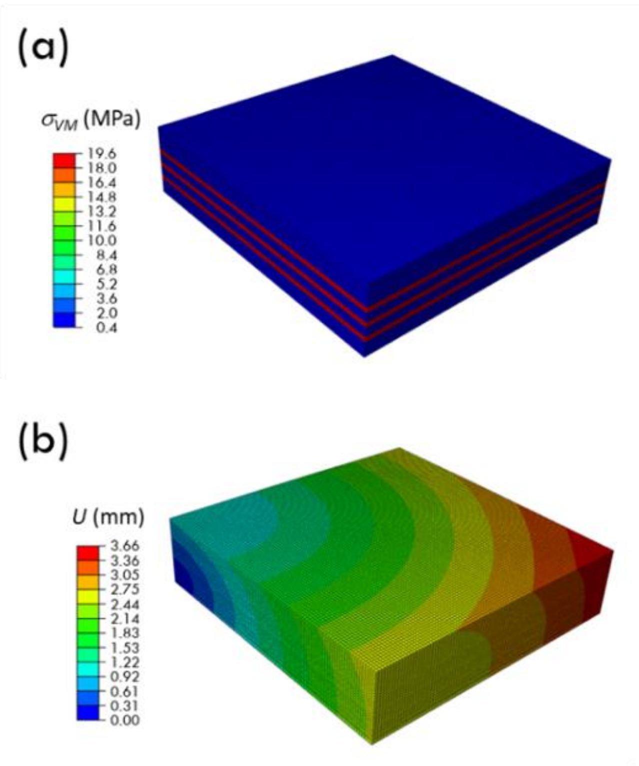


**Figure 11**. Simulation Result for Von Mises stress (a) and displacement (b).

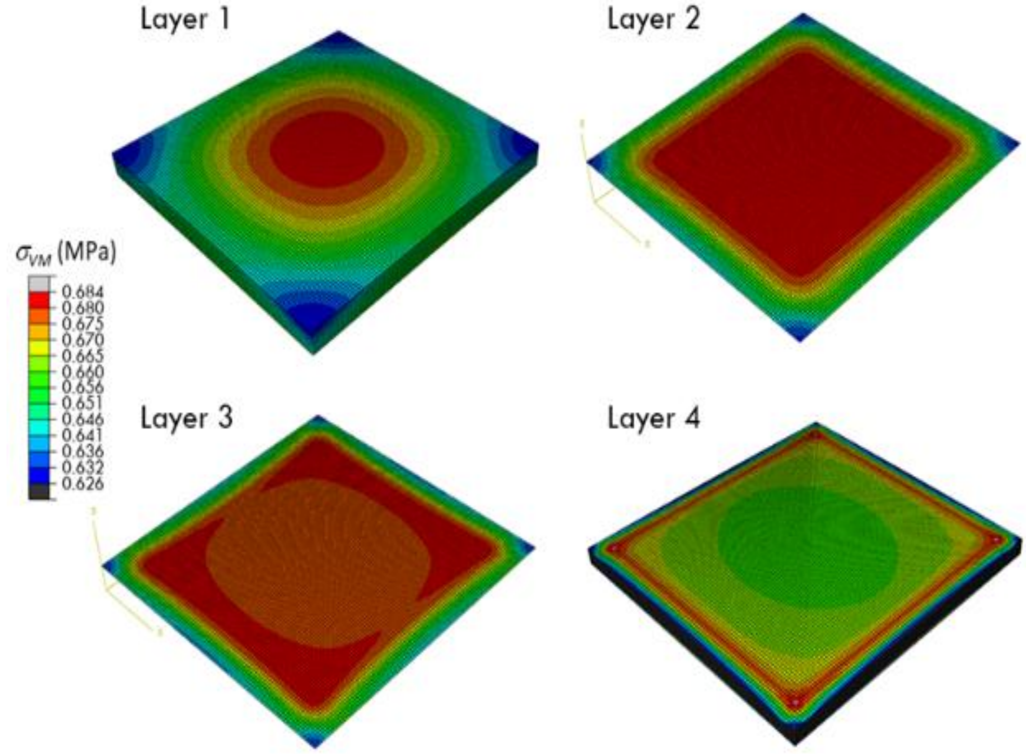


**Figure 12**. Stress distribution in rubber layers.

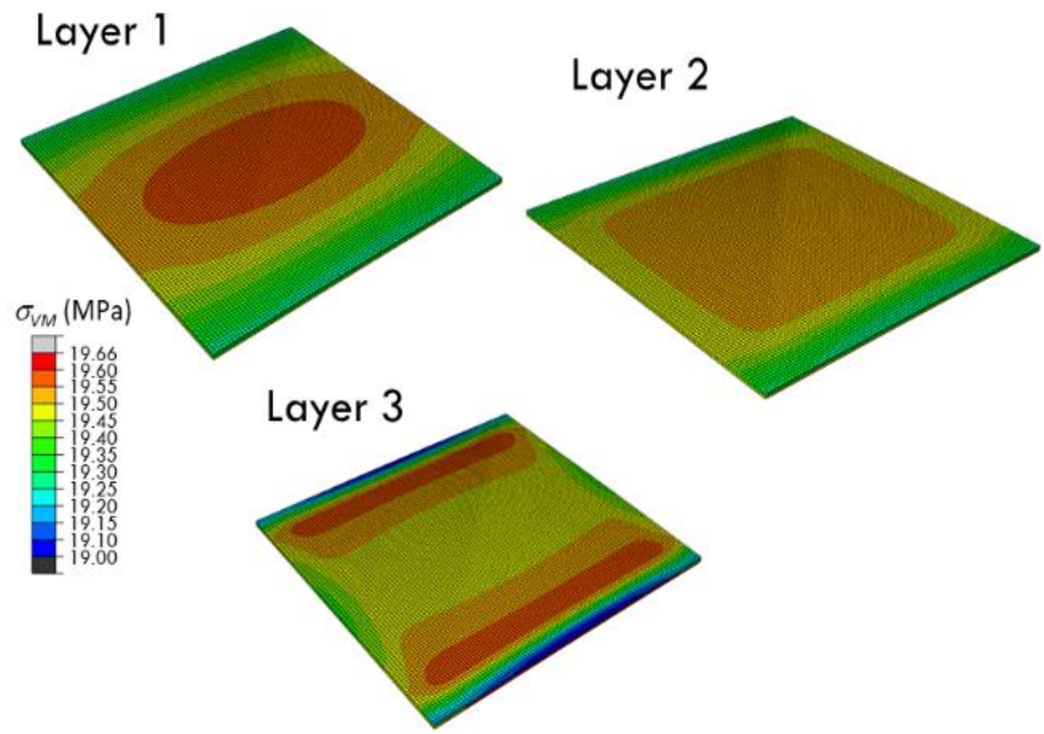


**Figure 13**. Stress distribution in woven fabric layers.

**Figure 14** shows the numerical simulation results for the model with hole damage. Stress concentration clearly appears around the hole. As the depth of the hole increased, the stress concentration becomes higher. With a damage hole of 4 mm deep, the maximum stress for a structure is 20.2 MPa in woven fabric. The maximum von Mises stress value is similar to the model without hole damage (19.7 MPa). This result indicates that the damage in the rubber does not influence stress distribution so much as long as the woven fabric is not broken. In the case of 7 mm deep hole damage, the maximum von Mises stress is increasing drastically up to 49.4 MPa. This might happen because the first layer of woven fabric has broken. Thus, the structure bearing the load is not effective anymore. Note that the maximum von Mises value has over the ultimate tensile strength of the woven fabric, which means the hole damage will potentially propagate to obtain new stress balance. In the case of 10 mm deep hole damage, the maximum stress value is 50.3 MPa. In this case, two layers of woven fabric have broken. The damage is also expected to propagate rapidly. **Table 3** shows the maximum stress and safety factor of the rubber dam for different deep holes.

In terms of the design process for the inflatable rubber dam, the appearance of woven fabric is critical to bear excessive external loading. The selection of favorable materials for woven fabric is key to obtain a strong rubber dam. For maintenance issues, an inspection of a hole and another type of damages such as scratch must be conducted carefully. Those damages must be found during the inspection process before the damage becomes too deep so that the woven fabric is broken. In fact, corrective maintenance after the woven fabric is broken will not be effective since the woven fabric is difficult to be replaced. Even though the woven fabric at a certain position can be replaced, the typical stress distribution will be much different. Thus, another potential damage in the same location might occur.

**Table 3**. Stress Concentration of the woven fabrics for Various Crack Depth

| Crack Depth (mm) | Maximum Stress (MPa) | Ultimate strength (MPa) | Safety factor |
|---|---|---|---|
| No crack | 19.7 | 45 | 2.29 |
| 4 | 20.2 | | 2.22 |
| 7 | 49.4 | | 0.91 |
| 10 | 50.3 | | 0.89 |

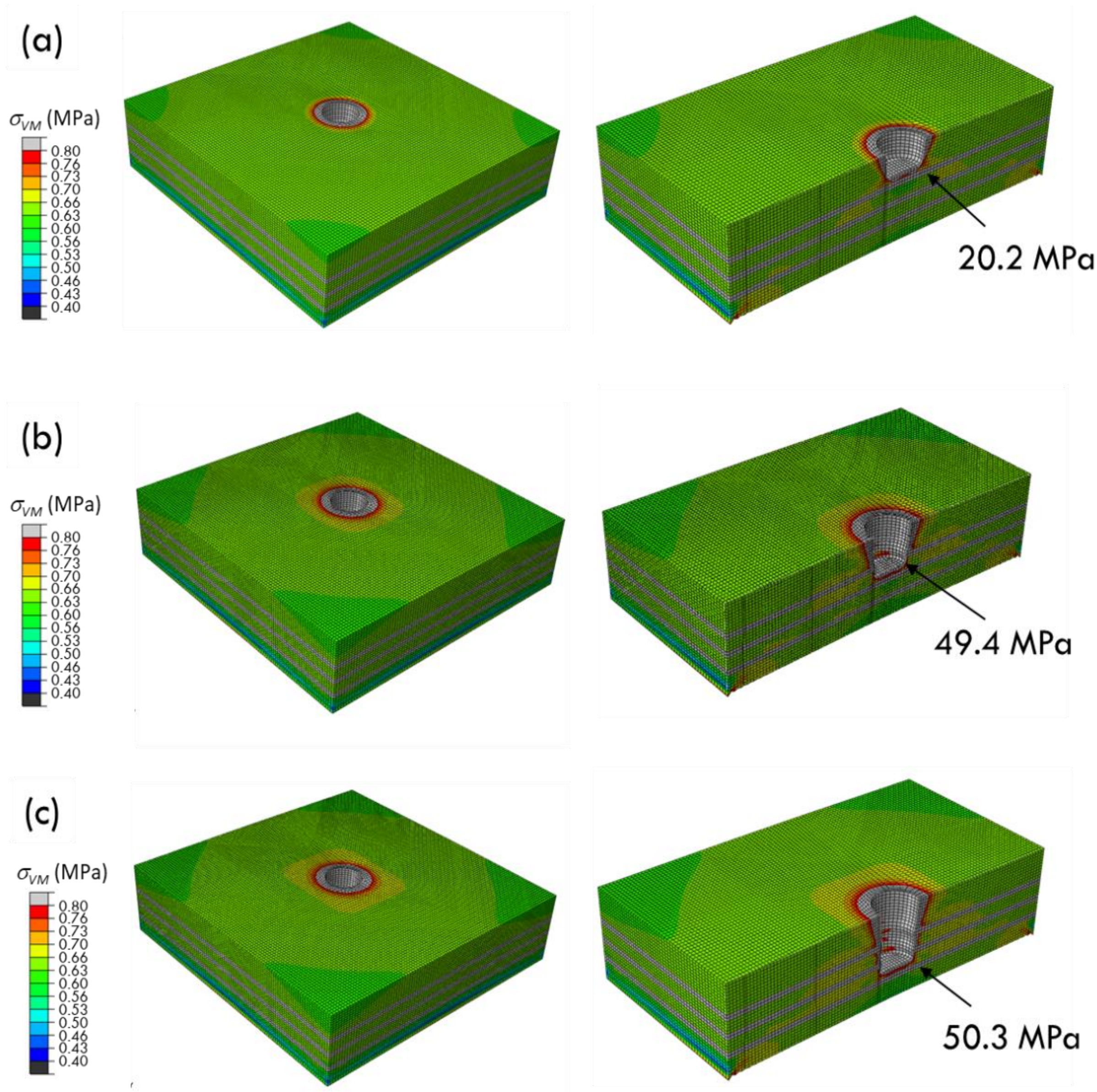


**Figure 14**. Simulation Results for (a) 4, (b) 7, and (c) 10 mm of deep crack conditions.

## 5. CONCLUSION

After conducting material testing, we found that material properties of the rubber dam used in Tongoloka district have been degraded up to 50%, which makes the rubber dam currently prone to failure. With the current operational load, by extrapolating the properties' degradation of rubber dam material, the rubber material is expected to reach its limit in 6 to 10 years depending on the selected failure criteria. The lack of maintenance for the rubber dam material adds risk to the calculation as deep hole damage was found in the rubber dam body. By performing further finite element analysis for rubber dam membrane with deep hole damage, it was found that hole with a depth of 7 mm may cause the failure of the membrane. This occurs because, with this depth, two woven fabrics as reinforcement cannot effectively bear the operational load of the membrane. Thus, the appearance of the hole must be considered carefully. This finding will be useful for designing membrane for a more reliable inflatable rubber dam.

## 6. ACKNOWLEDGEMENT

This paper is partially funded by USAID through Sustainable Higher Education Research Alliances (SHERA) program under grant number IIE00000078-ITB-1.

## 7. AUTHORS' NOTE

The author(s) declare(s) that there is no conflict of interest regarding the publication of this article. Authors confirmed that the data and the paper are free of plagiarism.

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