Damage to wood-beamed roofs of biogas tanks – causes, experience and recommendations

Summary

During the last a little less than four years the author examined damage (collapse) of wooden roofs of vessels (digesters, post-digesters, digestion residue stores) of 21 biogas plants. The lifetime of these plants in the federal states of Mecklenburg-Western Pomerania, Brandenburg, Schleswig-Holstein, Lower Saxony and Rhineland-Palatinate was between 5 months and 9 years.
Up to that time, no reports, documents, facts or figures published on such damage events had been known. The examinations were supported scientifically by Prof. Dr. rer. nat. Claudia von Laar of the Hochschule Wismar and Dr. Constanze Messal from the company MICOR, Laboratory for microbial processes and materials science in Rostock.
It was found that the interactions of the damage mechanism in the wood under the action of aggressive media were very complex and could not be explained with reference to the available know-how relating to so called maceration.
Furthermore, stability, design and quality issues of the use of timber in the conditions found in these vessels were considered.
This paper discusses the present results of the examination and describes the effects of chemicals on the properties of timber as far as is known today and the issues in relation with the stability calculations of these timber structures.

1 Technical and scientific preliminary remarks

1.1 Wooden roof structure

The wooden roofs known to the author consist normally of 15 - 40 joists /rafters of coniferous timber (fir/spruce) which in the shape of a star rest between the wall of the vessel (on a metal console, joist hangers, recesses or on the edge of the vessel) and a center pillar of concrete or timber of usually 10 - 15 m length. Nailed onto these joists are – partly with an air gap – form boards which in some cases are covered with fleece matting (except on digestion residue stores). Deviating from the above description, there are structures in which the wooden formwork is only partially installed or in which the formwork/fleece is replaced by string netting (mostly on digestion residue stores).

Figure 1: Inside view of a digester under repair

Supporting the loads of the gas storage and weather protection film and of man loads during the construction of the plant or during repairs or other disruptions (e.g., power outage), the wooden joists also perform a stability function.
A second function is, together with the formwork and the fleece layer or netting to provide a surface on which the so called thiobacteria can settle.

1.2 Chemical processes in biogas vessels

Biogas is a very complex mixture of different gases, chemical compounds and elements that depends on many factors. In addition to the main components methane (CH_4) and carbon dioxide (CO_2), "by-products" include nitrogen (N), oxygen (O_2), hydrogen sulfide (H_2S), hydrogen (H_2) and ammonia (NH_3). Other elements and compounds can be detected in the substrate (e.g., phosphates, ammonium, chloride, sulfate, nitrates, calcium, potassium, and silicon).
The qualitative and quantitative presence of the different elements and compounds depends on a multitude of factors, e.g., the composition of the digestion substrate and the operation of the plants and has not fully been understood as far as I am aware.
Hydrogen sulfide (H_2S) is probably the most critical of these by-products because it is highly toxic and sulfuric acid – which must be removed - is produced when hydrogen sulfide is burnt in the gas turbines.
In addition to the so-called external desulfurization (not considered here), the function of the wooden roof, including the formwork/fleece/netting as settlement surface for thiobacteria is of importance here. Thiobactria, also known as sulfur oxidizing bacteria/sulfur bacteria/sulfuricants, belong to the gram-negative, non-spore forming bacteria, of which 8 known species exist. The different species settle successively at different pH values and when substrate is available in sufficient quantity until, at pH below 1, only T. thiooxidans is viable [29]. During that process, which is referred to as internal desulfurization, the thiobacteria consume – as a welcome phenomenon - the hydrogen sulfide produced by the process of digestion as source of energy and – under addition of atmospheric oxygen which is blown into the vessel - produce elementary sulfur and sulfate. A major

disadvantage of this process is that sulfuric acid and hydrosulfuric acid are also produced.
This can be described by the following chemical equations:

Equation 1: $2\ H_2S + O_2 \longrightarrow 2\ H_2O + 2S$

(the desirable process of eliminating H_2S: production of sulfur and water by blowing in atmospheric oxygen)

Equation 2: $H_2S + H_2O \longrightarrow H_3O^+ + HS^-$

(an undesirable but permanent process in the digester space: Production of acidic and corrosive hydrosulfuric acid by dissolution of H_2S in water, which is present in abundance in the digester)

Equation 3: $S + H_2O + O_2 \xrightarrow{\text{Thio`s}} H_2SO_4$

(the process that is most critical: Production of sulfuric aid from sulfur and oxygen assisted by thiobacteria)

The fact that these chemical processes are highly corrosive to concrete and metals has been known generally, mainly also in waste water engineering, for decades [40].
The effects of acids on wood went unnoticed although there were numerous examinations and publications on the related topic of maceration and timber corrosion [32] – [39].
This provided the starting point for the examinations reported here.

1.3 Moisture and strength of wood

Wood is a hygroscopic material which absorbs moisture from or releases moisture into the environment. The moisture of wood depends on the moisture of the environment, mostly that of the ambient air: the drier the environment, the drier the wood becomes and the higher the moisture level of the environment the higher is also the moisture of the wood. In the case of the ambient air, there is a direct connection between the relative humidity of the air, temperature and the moisture of wood.
When the ambient climate (temperature and humidity of the air) remain relatively constant and act on the wood for a period of sufficient length, the moisture of the wood establishes at a certain level. This level is referred to as equilibrium moisture level (u_{equ}).
The wood moisture that establishes at 100% relative air humidity is known as fiber saturation moisture.
The relative wood moisture of spruce wood with an average bulk density r_0 = 300...430...640 kg/m³ is about 33 % (cell walls filled with water) at 100 % relative air humidity.
Thus, spruce wood of 25 % wood moisture (level for service class 3) contains about 100 kg/m³ water and at 33 % wood moisture about 140 kg/m³ water more than kiln

dry wood. Thus, a joist of 0.1 x 0.3 x 10 m carries an additional load of about 30 kg at 25 % wood moisture and of about 43 kg at 33 % wood moisture. Freshly harvested coniferous timber contains, on average, 55-70% water relative to that of kiln dry timber. The core contains about 35-50%, the sapwood about 100-150% water [25]. The u_{max} level for spruce is around 200 % (cells filled with water = wet storage).
Aside from the increase of the deadweight of timber parts with rising wood moisture it is also known that wood looses strength and bulk density at higher moisture levels. Practical values for calculation are provided in [26]. This means that mathematically the bending strength as the relevant parameter for wood joists drops by approximately 32% when the wood moisture increases from 25 % (service class 3 level) to 33 % (fiber saturation).

2 The damage cases

Following are brief descriptions of a few selected cases of damage.

2.1 Mecklenburg-Western Pomerania – May 2012 (1st examined case)

Breakage of three rafters after a service period of about 6 years. Another four rafters broke when the plastic film roof was removed for repair so that the complete roof on the digester had to be replaced in February 2012. Inspection in May 2012. Because broken rafters could be seen in the sight glass of the second digester, that roof was also replaced in August 2012. The timber parts from that second digester roof were examined by Prof. Claudia von Laar, Hochschule Wismar. The results of the examination available so far have, in part, been published in [4], [6] and [8] and can be downloaded from the author's homepage.

Figure 2: View of the broken rafters from the digester

Figure 3: New roof on digester 2

2.2 Brandenburg – July 2013

Figure 4: View of the demolished rafters from digester 1

Figure 5: View of the digester after the collapse/partial removal

Slippage of a rafter off the holder system at the vessel edge of the digester after a service period of about 5 years in May with the consequence of the gradual failure and fall of further rafters to the complete collapse when Padelgigant engaged the formwork/fleece layer. Breakage of more rafters during removal of the structure. Inspection at the time of removal in July 2013, published in [7] and [11]. Serious stability defects.

2.3 Schleswig-Holstein – December 2013

Breakage of totally 6 rafters in the area where rafters were changed after about 3.5 service years in connection with the removal of the plastic film roof after a power failure in October 2013. The rafter change had been planned so that not the complete roof structure had to be removed when the stirrer needed repair or replacement. No stability calculation available for the rafter change.

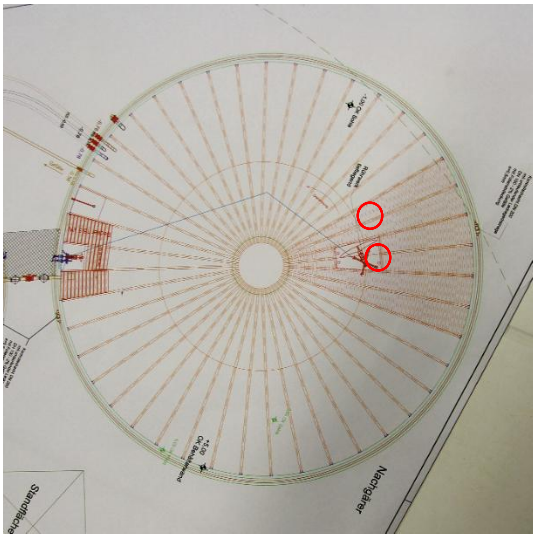


Figure 6: Sketch of the post-digester; the red circles mark the points where the rafters broke

Figure 7: Rafter breakage at the change point

Figure 8: Detail of the broken rafter

2.4 Mecklenburg-Western Pomerania March 2014

Breakage of 3 rafters (another 2 rafters partly broken) of a digester residue store after only a few months of service (after a storm).

Figure 9: View of the breakage point after opening it

Figure 10: Recovery of a broken rafter

2.5 Mecklenburg-Western Pomerania July 2014

Breakage of a rafter in a digester in the area of a working platform after 2.5 years service. The platform serves for necessary work (e.g., replacement) of the stirrers beneath.

Figure 11: View of the breakage with remains of the working platform

Figure 12: Visible sag of the rafter in Figure 11

Figure 13: View of the point of breakage

Figure 14: View of the second working platform

No available stability calculation of the rafters with the working platform.

2.6 Rhineland-Palatinate May

Failure of several roof joists of a combination biogas vessel after about 1.5 years of service. Breakage of the joists and slippage off the holders. Distinct design defects.

Figures 15-18: Different damage cases

3 Results of the inspections and examinations

3.1 Visual findings

It was seen in all objects examined that the timber components had different deposits of greatly varying appearance and thickness. A distinct difference was noted between timber components exclusively exposed to the gas produced in the digester and others in more or less close contact with the digestion substrate. The color of the deposits varied from light yellow to dark, almost black hues. Most deposits were saturated with water. The following was noted, in addition:

- Blackish/brownish discoloration of the wood surface
- Fraying of the wood
- A mostly short-fiber breakage pattern of the rafters
- In some cases a visible sag of the rafters

Figure 19: Blackish, frayed surface

Figures 20-23: Extremely short breakages

Figure 24: Sulfur deposits, from thin and crusty…

Figure 25-26: …. to a thickness of several centimeters

3.2 Results of the chemical and microscopic examinations

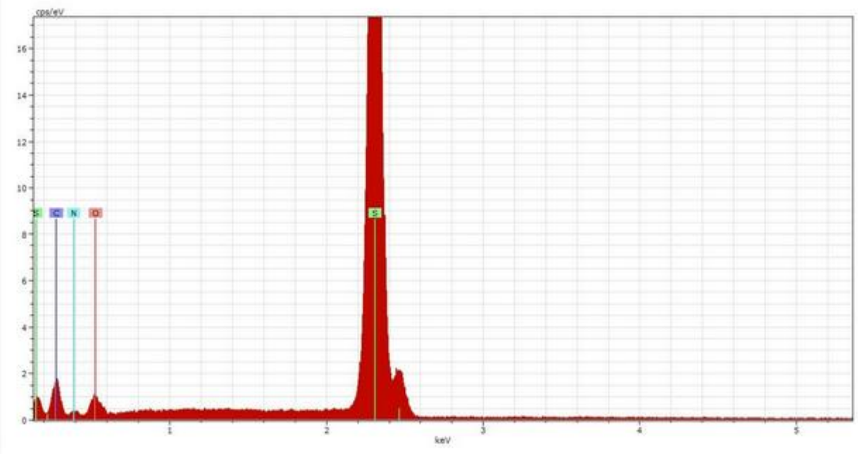
The examination of the timber parts from the damage cases for their contents of chemical elements and compounds shows a highly differentiated stress pattern. The pH values also vary among objects and the places where the parts had been placed in the structure. Table 1 below shows typical values of totally 45 wood samples from 16 damage cases.

Table 1: Bandwidth of the chemical analyses of wood samples

	Nitrate	Sulfate	Chloride	Ammonium	Phosphate	pH
Content in mg/kg wood	10 – 50	500 – 24000	0 – 550	50 – 1500	0 –50	2.1 – 7.8
(Reference level from [6], [8])	(10)	(100)	(100)	(20)	(20)	abt. 5,0

The analysis showed that the samples obtained from fracture zones and visibly

damaged wood sections of digesters and post-digesters had a distinctly higher load of the above elements and the pH value was clearly in the acidic range. Only wood samples from digestion residue stores or samples that had had a short dwell time in the vessel fared distinctly better.
The REM/EDX (scanning electron microscopic energy dispersive X-ray analysis) examinations of the deposits showed a distinct dominance of sulfur in the yellow deposits whereas wooden parts that had had contact with the digestion substrate proved to consist of a mixture of several elements.



Spektrum 1: Dominanz des Elementes Schwefel

Figure 27: Analysis of the yellow deposits

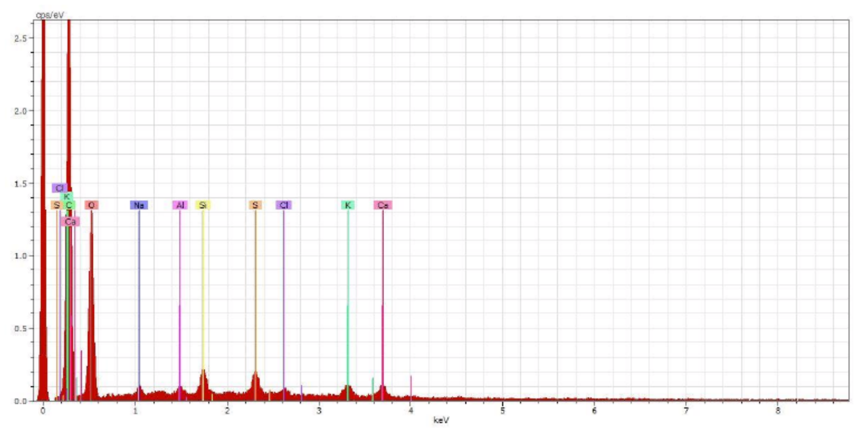


Bild 27: EDX 1-3 Randbereich der 2. Probe aus Bruchzone, wiederum Anreicherung von Schwefel, Natrium, Chlor, Kalium sowie Silizium und Calcium

Figure 28: Analysis of a rafter after extended exposure to digestion substrate

These results prove beyond doubt that the wood had been exposed to what is called an “acidic attack“, i.e., presumably an acid-hydrolytic degradation of the carbohydrates cellulose and hemicellulose.
According to Schwar [39], the “action of salt solutions with acid reaction cause

decomposition preferably of hemicellulose. Given the situation that most of the salt solution can be found in the primary wall and secondary wall 1 and the concentration of hemicellulose is highest in that region, strength must have suffered mostly there in the presence of appropriate pH levels. If stress > stressability (resistance), damage, in this case corrosion (loss of the fiber composite) and reduction of the strength of the wood in the near-surface, is unavoidable.“

Looking at the results of the microscopic examinations obtained so far (incident light and transmission electron (TEM) microscopy), damage to the so called middle lamella is responsible for the dissolution of the association of cells. A middle lamella is a thin plasma-like layer of pectins between adjoining plant cells. This structure causes adjoining cells virtually to stick together. The mechanism of this damage has not been understood so far.

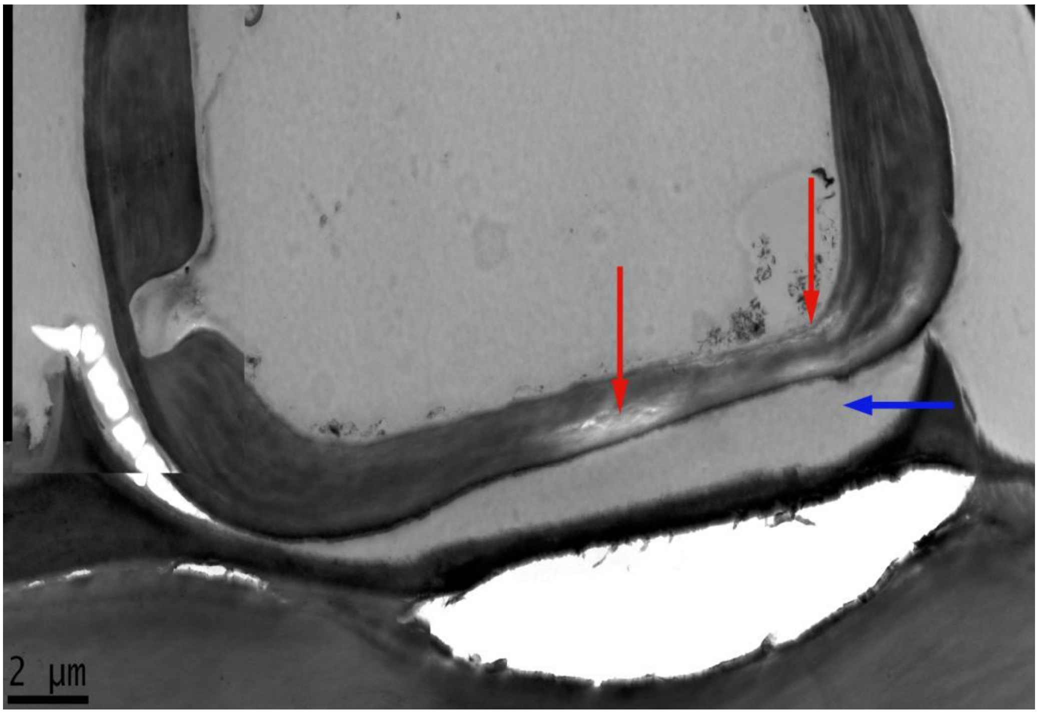


Figure 29: TEM image by Dr. Tobias Huckfeldt, Hamburg:
Almost complete detachment in the area of the middle lamellas /S1 (⟵) also delicately structured modifications of the cell wall (↓). (The white areas are artefacts), Source: Claudia von Laar

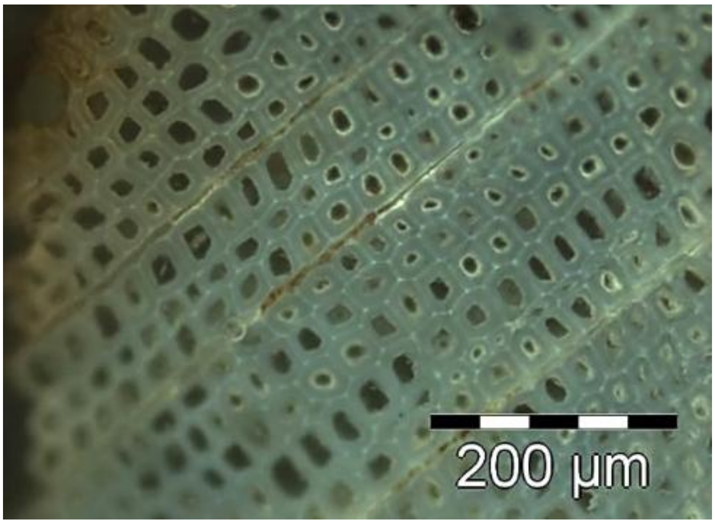


Figure 30: Light-microscopic image by Dr. Messal with visible dissolutions of associations of cells and immigrated substrate

Another important result of these microscopic examinations was that the damage of the wood is by no means caused by fungal or bacterial organisms.

A new chemical problem has been identified which can be causal to the wood damage.
In some plants, ferrous chloride is added to the substrate to improve the removal of sulfur. This chemical process can be described by the following equation:

Ferrous chloride precipitation reaction: $FeCl_2 + H_2S \rightarrow FeS + 2\ HCl$

Hydrochloric acid which is known to attack wood is formed by this process. This is possibly indicated by the high chloride concentrations in some examinations. This process has not been examined or detected so far.

3.3 Wood moisture and bulk density

Wood moisture was determined by the DARR method [17].
The values measured directly after removal of the rafters were between 110 and 150 % rel. humidity; it was still as high as between 70 and 100% in wood after 4 weeks of outdoor storage.
This means that the relative moisture of the wood was still distinctly higher than the expected equilibrium moisture of about 33 %.
This high moisture level has several causes:

- The air inside the vessel, which is almost completely saturated with water vapor, i.e., the wood takes up moisture nearly to the point of fiber saturation
- Water from the chemical processes of desulfurization (see equation 1 in ch. 2.2)

- The hygroscopic action of the salt compound layers on the wood
- Condensing water that drips from the gas storage cover.

That water puts the rafters under a major additional stress that affects their deflection and bending stress.
The bulk density figures obtained were mostly in the middle bracket; only a few were in the lower range of the standard bulk densities of spruce and as such were not much of a problem. However, because the bulk densities of spruce differ widely according to where the sample is taken from the trunk (inside-outside, bottom – top), reference samples of the wood before installation in the plant would have had to be obtained for reference; but these were, of course, not available.

3.4 Assessment of the stability calculations and the timber quality

The stability calculations of the failed roof structures were requested in all 21 damage cases. The regulations regarding stability calculations are quite different in the different states; in some states they must be verified by a certified structural engineer.
In almost all cases studied the stability calculations had not been available to the plant owners at the time building work started or not even at the time of the examinations; partly they were prepared only upon request after the damage had occurred. All calculations stated that all requirements had been complied with (with the exception of the usability = deflection, which was exceeded in most cases but that was rated as not being of any concern).
Common to all stability calculations submitted was that they did not assume the real conditions and stresses of the timber components in the vessels and therefore were all judged to be wrong.

Reasons:

- For the calculations according to EC5 (DIN EN 1995-1, Eurocode 5 Holzbau) and DIN 1052 (Holzbauwerke – Berechnung und Ausführung), accordingly, the rafters were all placed in service class 3 (NKL 3). DIN 1052 characterizes service class 3 as follows:
  "*Service class 3: It embraces climate conditions resulting in higher wood moisture levels than specified in service class 2, e.g., for structures exposed to weather.*
  Note: In service class 2, the mean moisture content of most coniferous wood types does not exceed 20 %. In service class 3, the moisture at the time of installation should not be higher than 25%."
  As stated above, the relative moisture of the wood was found to be up to 150 %. Assuming a certain lack of knowledge of the above-mentioned waster stress conditions, at least the equilibrium moisture of 33 % would have had to be assumed for the calculation. As far as I am aware, this is not supported by the standard stability calculation programs so that

„manual“ calculation would have been required.

- The assumptions for additional loads such as
  - Additional water in the wood
  - Deposits of sulfur, etc., also containing water

  were not assumed or the assumptions were lower than justified.
- No reduction to account for the lower bulk density and wood strength as a result of the high moisture levels of the wood was allowed.
  The fact that temperature also affects the wood strength may deserve a marginal mention here.
- No reduction of the wood strength due to the chemical processes had been made (which may be assumed not to have been known by that time).
- In some cases,
  - Only service lass 2 had been assumed for the calculations
  - The dimensions of the depth of support on the edge of the vessel were wrong
  - An integrated change at the rafter had not been considered in the calculation
- The stability calculation contained the statement: “The rafter roof cannot be walked on.“
- In several cases the dimensions of the rafters had been changed by the construction firm without authority and without reference to the calculation.

Figure 31: Service class 3???

Figure 32: Support depth: 8 cm calculated,
5 cm theoretical, 2 cm in practice

Figure 33: Heavy sag

Figure 34: Extensive wet deposits

The Calculations done by a partner firm on the basis of the real loads for all examined constructions showed that the permitted bending stress was exceeded substantially and deflection was unacceptable in several cases.

Another problem is that known properties of wood as a building material had not been heeded.
Wood changes its shape as a function of moisture (shrink and swell). That uneven swelling during the uptake of water is the reason of „warping“ or distortion of the joist.
Stability calculations of such timber parts (or bending joists) always presume that there is no way in which a part can move sideways, i.e., that lateral movement or displacement of the joist is neither possible at the point of support or along the joist. Otherwise the resulting torsional force may cause tilting (bending-torsion-collapse). Rafters 10 - 15 m in length simply must warp under the given conditions. That means the stability calculations would have had to make allowance for lateral bracing. As it is, a precondition for the validity of the verified stability calculation, i.e., the requirement of the “continuity of the compression chord“ was disregarded, which makes the calculations defective.

Other requirements of DIN 4071 such as, for example, presence of knots and spiral grain, had also been disregarded in some cases. It must be stated as a result of the examinations that the quality of the timber did not play a decisive role.

In addition, it should be mentioned that chemical wood protection was not provided in any case; it had not even been considered. That would have been an issue under applicable building regulations because established technical building regulations (in this case DIN 68800-1 and 2) had not been considered and would have had to be excluded in the contract. In my view, that would have had no effect anyway.

4 Summary

To begin with, it should be mentioned that the results reported above are those of „only“ 21 damage events.

Despite that, the results make the following clear:

- There are general doubtful problems and backlog as regards stability calculations and wood quality in the professional execution of the structures.

- The combination of sulfuric acid and high wood moisture causes ingress of the sulfuric acid in the wood by diffusion. This results in a general biochemical process by which the structure of the wood is attacked and destroyed.

  The associated weakening of the strength of the wood had not been known to be as high as it really is and therefore was not considered in the stability calculations. The extent to which this can be expressed in numbers is not known.

The damage events examined so far illustrate the complex nature of the issue and the connection between the actual gas production and the undesirable side-effects.

Many questions as to the underlying causes and, more even, the consequences and alternatives remain unanswered.

The exact number of biogas plants in Germany is not even known. The statistics published by Fachverband Biogas e.V. put the figure at about 7900 biogas plants by the end of 2013 [28]. The number of vessels (digesters, post-digesters, digestion residue stores) belonging to these biogas plants remains guesswork. And how many of these have a timber roof? How are these roofs constructed? What is he number of planning and manufacturing firms, and what are their professional qualifications? How many damage cases are not known and have not been reported? Except the 21 cases examined, the author is aware of about another 30 such cases. I presume the number of undetected cases is considerable.

The scientific insight in the causes, which should actually provide the basis on which many of the questions asked can be answered, is also still in the nascent state, firstly, to find the detailed causes of these cases of damage and, secondly, to come up with viable solutions. To my knowledge, there are (regrettably) no such research projects in the pipeline.

Based on present know-how, actually no safe control or predictability of the failure of a timber roof is possible.

The following points should be considered in any case to take some kind of precaution:

- Control of the availability and verified (on the basis of the provisions in force in the respective state) stability calculation of the roof before the building permit is issued
- Control of legacy plants to ensure that stability calculations are available and checking the calculation by another expert who is familiar with the problem (assumption of real loads)
- Regular visual inspection of the deflection and the points of supports
- Testing the load bearing capacity of rafters as part of repairs, for example, by subjecting the rafters to double man-load midfield
- Taking of wood samples and chemical analysis of the samples during planned opening of the roof

Irrespective of that, examinations of other construction methods (tension straps) and materials (e.g., GRP beams) should be encouraged to provide replacement solutions for legacy plants.

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