# Failure of Steam Piping Structure

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**Abstract:** The aim of paper is an analysis of the causes of an accident that occurred in the piping system as a result of the failure of the control system and subsequent uncontrolled operation of the steam boiler for several hours. Cracks were found in many places of the pipe system of the boiler after it was shut down, and in one place the pipe was completely destroyed. The temperature change of a piping system was performed by the finite element method. Quantification of residual stresses by the hole drilling method were performed to assess possible causes of the failure of the piping system. From the obtained results, it is clear that the temperature change in the piping system cannot be considered the main cause of the pipe system failure. High levels of residual stress was identified at the site of the breach were found to be the most important cause of the failure.

**Keywords:** Welded structure; Failure; Stress analysis

## 1 Introduction

The steam boiler, waste collection bunker and the flue gas cleaning equipment are the main technological units of the waste incinerator for energy recovery of municipal waste. The heat produced in the form of steam is used for technological needs of the incineration plant as well as for the central heat supply of residential buildings and also for generation of electric power. In order for the complex technological units to function properly, it is necessary to constantly monitor and evaluate the operational parameters. The most common method used to set optimum operating modes of steam boilers is to control changes in temperature and pressure, where pressure of the medium can change independently of its temperature. Thus, acceptable changes in the temperature of the medium used during startup and shutdown processes are to be determined [1]. Modern automated control systems of steam boilers must also enable to solve the problem of combustion of combustible (explosive) materials contained in municipal waste during operation. For this reason, the design of steam boilers already places great emphasis on the analysis of temperature fields. For steel welded structures operated at high temperatures or in a humid environment, it is necessary to pay close attention to issues related to corrosion, creep. Prolonged exposure to elevated temperatures of ferritic steel boiler pipes reduces their service life and is often a major cause of damage [2]. Most cracks occur in the bent parts of the tubes which confirms the possible presence of residual stresses caused by bending. Insufficient heat treatment (e.g. annealing) does not release stresses [3,4]. As the knowledge gained from practice shows, failure of load-bearing structures may occur not only due to operating load, material fatigue, corrosion, but also due to reconstructions. Duda et al. [5] describes the procedure of the boiler failure analysis that occurred during the reconstruction works. The numerical and experimental modelling methods are used to document the conclusions. Although modern computer simulations are used in the design of complex devices, it is important to point out that defining boundary conditions corresponding to operating conditions is very difficult in such cases. The quantification of some effects in these situations by other than experimental

methods is impossible. In identifying failure in welded steel structures, comparative analysis of the material taken from the location of the failure with the new material is often used to determine the causes. In this case, however, the equipment operator had no new material available for comparison. Numerical modelling is very difficult to use for the assessment of the operation safety of a steam boiler after its failure, as it is a steel welded structure. In these cases, it is almost impossible to define the boundary conditions so that they correspond to the actual conditions, i.e. to take into account possible assembly and manufacturing inaccuracies, the operating load history as well as thermal analysis. It should be pointed out that the analysed steam boiler (Fig. 1) is a part of the incinerator, where unforeseen thermal shocks such as burning of explosive material and the like often occur. For this reason, the authors proposed a methodology for assessing the further safe operation of the steam boiler on the basis of available data, i.e. supplied drawing documentation, description of the accident, material taken from the place of failure. First of all, measurement of the residual stresses in the materials collected from the damaged area were carried out. The numerical modelling was performed using the submitted design documentation, visual inspection and information on the process of the failure.

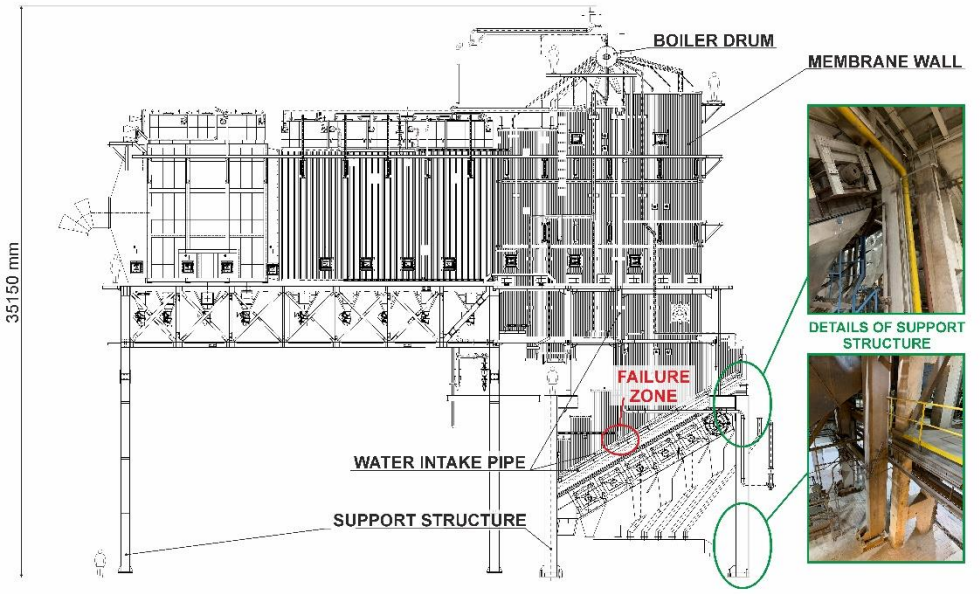



**Fig. 1** Schema of analysed steam boiler.

## 2 Description of the steam boiler accident

Piping systems of steam boilers are loaded by internal pressure and also by thermal stresses. These are welded steel structures for which, when assessing their durability and safe operation, it is necessary to consider the increased levels of tensile stresses in the vicinity of welds caused by welding technology. In many cases, a failure occurs only around the welds. The steam boiler under consideration was in operation for less than four years. During the previous operation of the steam boiler there was not observed any significant improper functioning, which could predict a dangerous situation or failure. Despite these facts the failure of the steam boiler occurred within a few hours. Firstly, there occurred a failure in the control unit followed by the loss of information on the key parameters of the combustion

process as well as boiler control itself, namely, information on the water level in the drum, the steam flow, pressures and the temperature in the combustion chamber followed, and then failure of the cooling towers control and a water intake control valve. As the control unit was not functional, the amount of water in the piping system decreased because the supply valve was blocked. This fact was confirmed by the drop of water level in the boiler drum below the critical level within 90 seconds of the control unit failure. After the control unit failure, it was found that 16 input-output cards of the control unit were inactive. Based on the diagnostics of the control system it was found that the control unit failure was caused by the damaged converter. After diagnostics and necessary repairs, the system was ready to restart in less than two hours. After the system was started, the water intake valve suddenly fully opened due to the failure of the system's security features. It should be pointed out that if the water level in the boiler drum falls below a critical value (this state occurred immediately after the control unit failed), the water piping system must not be filled with water. Within two minutes the water valve was manually shut and the shutdown of the steam boiler started. The above-mentioned procedure was in accordance with the operating manual. Despite fast intervention of the service personnel within approx. 10 minutes after the system start-up, a leak of steam on both sides of the boiler was observed. Works on the emergency shutdown of the steam boiler continued until the boiler pressure was reduced to atmospheric pressure. This process took about 7 hours. After the boiler had cooled down, the side walls of the boiler were uncovered. Fig. 2a shows a part of the membrane wall and water intake pipe. A lot of cracks were identified during the inspection of the piping system, especially on the welds of the water intake pipe (Fig. 2b).

(a) (b)

**Fig. 2** (a) Membrane wall and water intake pipe, (b) cracks of welds on the water intake pipe.

On the right side of the boiler, the connecting part of the pipe leading from the water intake pipe to the pipe of the membrane wall was completely torn off (Fig. 3a). Fig. 3b gives a detailed view of the pipe torn off from the connection part.

(a) (b)

**Fig. 3** Weld failure of the water intake pipe: (a) general view, (b) detailed view.

The initial conclusions on what possibly caused the boiler piping system failure were drawn based on the above-mentioned facts. The most probable cause was failure of the control unit, which caused blockage of the water intake valve resulting in the lack of water in the piping system. The boiler subsequently operated in an uncontrolled mode (further waste burning). During that time individual parts of the piping system were exposed to uneven thermal stress leading to the initiation of cracks and subsequent failure of some welded joints. Due to the fact that the damaged parts of the piping system were repaired and the operation was restarted within several tens of hours, it was not possible to carry experiments on the damaged pipeline immediately. For this reason, the authors used numerical modelling method to confirm or refute the above hypothesis. The authors considered it essential to know actual mechanical properties of the used material (WNr. 1.0570), but also the residual stresses in the parts taken from the damaged piping system in order to assess their possible impact on the occurrence of the accident.

## 3 Numerical analysis of failure part of piping system

Numerical finite element modelling is used for stress and strain analysis in the design of welded steel structures. When analysing the steam boiler failure by numerical modelling, it is almost impossible to define boundary conditions so that they correspond to actual conditions, i.e. take into account possible assembly and manufacturing inaccuracies, the operating load history as well as thermal analysis. It should be pointed out that the analysed steam boiler is part of the incinerator, where unforeseen thermal shocks occur such as burning of explosive material. Numerical modelling is reasonable especially at the design stage of machines and equipment. Therefore, the authors performed numerical modelling on a model case where the boundary conditions were defined on the basis of the available information, i.e. drawing documentation, visual inspection and description of the accident. The impact of the temperature change was defined as the unit load, as the information on the temperature in individual parts of the steel structure is not registered by the operator. The change in the temperature was calculated in view of the change in the length of the vertical part of the water pipe, which caused the load of the analysed node III (Fig. 4). In numerical modelling, the material properties of the model were defined according to the drawing documentation. The numerical modelling was used to model only part of the water intake system where the weld failure occurred. Based on visual inspection it was found that the interconnecting pipe was welded at the locations as shown in Fig. 4. The numerical analysis was used for the verification of the effect of temperature on stress levels in the concentrator area. For this reason, only the linear static analysis was performed.

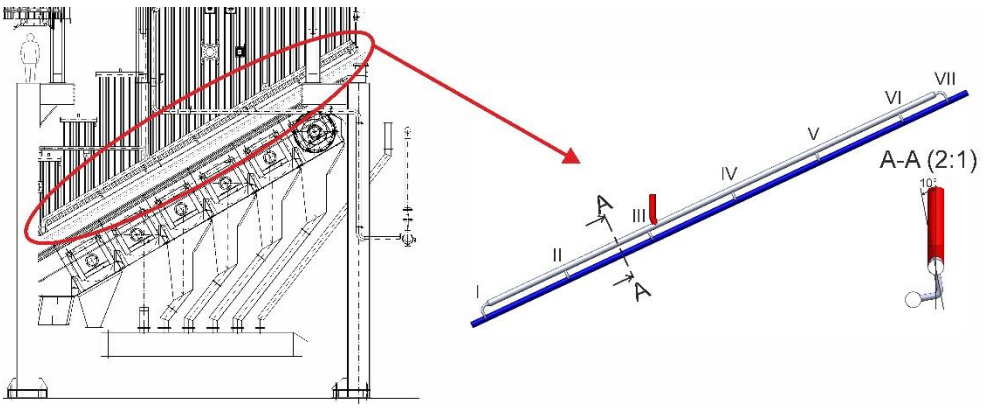



**Fig. 4** Model of analysed part of water intake system.

When defining the boundary conditions, it was taken into account that one part of the piping system was fixed (the blue tube welded to the membranes, Fig. 4), and the loading was caused by displacement of the pipe by 1 mm in the vertical direction (Fig. 4, red tube). Ansys software was used for the calculation. The finite element model was made from 987 968 nodes and from 494 709 volume finite elements with quadratic approximation. Fig. 5 shows a field of reduced stresses of the analysed part of the piping system. Fig. 6 gives a detail of the field of the reduced stresses at the site of the failure.

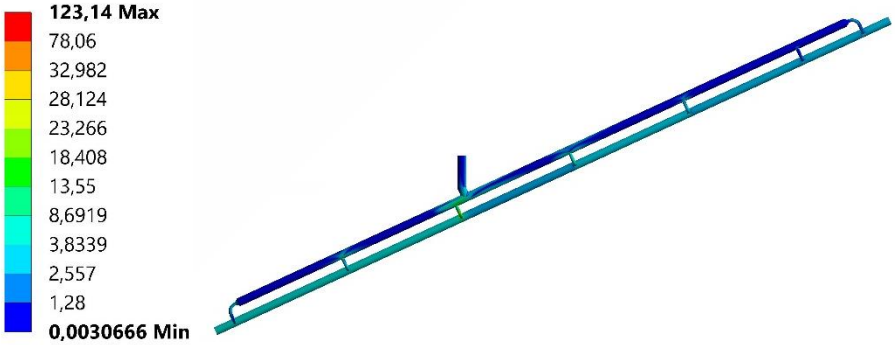



**Fig. 5** Field of the von Mises stresses of the analysed part of the piping system (MPa).

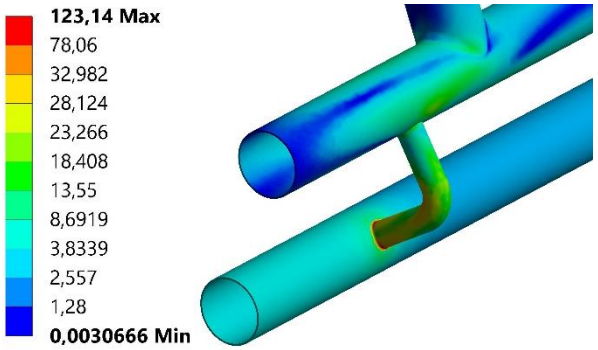



**Fig. 6** Detail of the field of the reduced stresses at the failure point III (MPa).

As can be seen from the results of numerical modelling for a simplified model case, the most significant increase in stress levels occurred in the interconnecting pipeline at point III (Fig. 4). The maximum value of the reduced stress corresponded to the failure point in the part of the interconnecting pipe in that location (Fig. 4). Increased levels were also identified in other locations by the FEM, where cracks in the welded joints also occurred. It should be noted that despite the good agreement of the results of numerical modelling with the locations of weld failure, the achieved numerical values of stresses cannot be considered accurate, because it was a simplified model case. It is a qualitative rather than a quantitative analysis.

## 4 Residual stress quantification

When assessing the lifetime and reliability of structures, it is important to know the levels of the residual stresses often associated with their failure or damage. The state of residual stress in supporting structure elements is the key factor of its behaviour in service. Therefore, knowledge of residual stress may predict signs of component failures and thus prevent and avoid accident. The residual stresses quantification by the hole drilling method was performed on a sample taken from the damaged piping system (Fig. 7). The drilling was performed by SINT MTS 3000 drilling machine (Fig. 8). The drilling process was performed in twenty steps for a blind hole with the total depth 2 mm in accordance with ASTM E-837-13a Standard [6]. The hole diameter was 1.6 mm. After each step, the magnitude of the released strains was recorded by the SPIDER measuring device with the strain gauge RY61-1.5/120S. Fig. 9 shows the drilling process on the inside of the pipe. The residual stresses and the directions of principal normal stresses were determined using Eval 7 program according to ASTM E 837-13a Standard. The view on all locations of strain gauges is given in Fig. 9.

**Fig. 7** Location of the sampling from the damaged piping system.

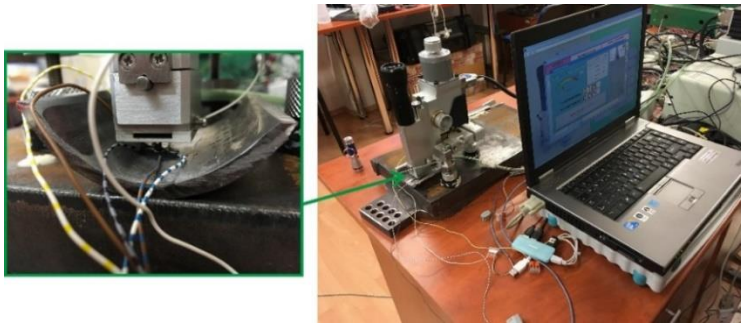
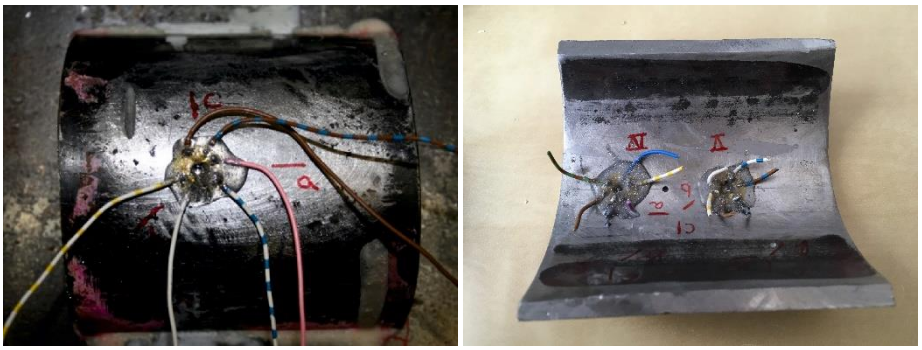


**Fig. 8** Drilling process on the inner side of the pipe.



(a) (b)

**Fig. 9** Locations of strain gauges: (a) outer side, (b) inner side.

Table 1 gives values of the residual stresses and their directions for each measurement point determined according to ASTM E 837-13a Standard. The angle $\varphi$ represents the deviation of the direction of the maximum principal stresses from the axis parallel to the pipe axis.

**Table 1.** Magnitudes of residual stresses and their directions according to ASTM E 837-13a Standard.

| Measured point | Tube side | $\sigma_{max}$ (MPa) | $\sigma_{min}$ (MPa) | $\varphi$ (°) | $\sigma_{red}$ (MPa) |
|---|---|---|---|---|---|
| I | external | 44,19 | -48,47 | -82,77 | 80 |
| IV | internal | 347,26 | 169,74 | 42,84 | 300 |
| V | internal | 246,14 | 126,01 | 57,61 | 213 |

High tensile stress levels were found by measuring residual stresses in the selected locations. Based on the above we can state that the values of the reduced stresses according to von Mises reached around 300 MPa, thus, achieving the yield strength of the used material. Despite the measured values of the residual stresses being relatively high, under normal operating conditions even such stress levels would not cause a steam boiler failure considering the fact that the steam boiler has been in operation for about 4 years. As a result of a sudden change in the temperature in the piping system due to the failure of the control unit, the resulting superposed stresses exceeded the permissible values, which led to the failure of the welded joint. All the above-mentioned shows that the high levels of the residual stresses in combination with the emergency condition had the highest impact on the failure.

## Conclusion

In the event of damage in welded steel structures, a comparative analysis of the material taken from the failure location with the new material is often used to determine the causes. In this case, however, no new material was available to the plant operator. For this reason, the authors proposed a methodology for assessing the further safe operation of the steam boiler on the basis of available data, i.e. supplied drawing documentation, description of the accident, material taken from the place of failure.

The numerical modelling on a model case was performed, where:

- The boundary conditions were defined on the basis of available information and the material properties of the model were defined according to the drawing documentation.

- The effect of temperature change was defined as the unit load, as the information on the temperature in individual parts of the steel structure is not registered by the operator.
- The good agreement of the results of numerical modelling with the locations of weld failure. However, the achieved numerical values of stresses cannot be considered accurate, because it was a simplified model case. It is a qualitative rather than a quantitative analysis.

Although the determination of residual stresses is currently well known, the authors consider their determination to be a quick tool to assess the current state of the structure after an accident. The main advantage is that, in addition to production technology, assembly inaccuracies and the like, they also take into account stresses from previous operation. Based on analysis of the residual stresses can be concluded:

- Despite the fact that the measured values of residual stresses are relatively high (300 MPa), under normal operating conditions even such a stress level would not cause a steam boiler accident, which is documented by the fact that the steam boiler has been in operation for about 4 years.
- As a result of a sudden change in the temperature in the piping system due to the failure of the control unit, the resulting superimposed stresses exceeded the allowed values, which led to the failure of the welded joint.
- However, high levels of residual stresses are determined, it can be stated that further operation of the device is not safe, or that the assessment will require further in-depth analyses, the implementation of which is often more time-consuming and costly.

The paper showed the steam boiler failure based on the measurement of the residual stresses in locations of the damaged structure, in this case of the piping system. Detection of possible causes by analytical or numerical modelling in such cases is almost impossible as it depends on many unknown factors entering the calculation. From the above conclusions as well as taking into account the previous trouble-free operation of the steam boiler, it can be stated that after the repairs of the identified cracks, the steam boiler can be operated safely.

## Acknowledgements

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