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REVIEW

of the PhD thesis by Benard Kiptoo Kipsang, MSc
entitled: *“Assessment of Fracture Development in Thick-Walled Elements of Power Boilers
after Long-Time Operation”*

The formal basis for this review is the resolution of the Council of the Discipline of Materials Engineering at the Silesian University of Technology, dated June 24, 2025, concerning the appointment of reviewers for the PhD thesis in question.

1. General characteristics of the thesis

The PhD thesis presented for review, authored by Mr. Bernard Kiptoo Kipsang, MSc, focuses on research into the influence of long-term operation under elevated temperature and mechanical loadings on fracture resistance and crack behavior in materials used in the power industry, particularly the 14MoV6-3 heat-resistant steel. This is an undoubtedly important issue. Currently, there is a strong emphasis on transitioning from fossil fuels to renewable energy sources, as well as on using fewer materials and natural resources to reduce carbon dioxide emissions. Despite this, conventional thermal power plants still play an important role in ensuring energy supply in Poland. Many of the units in these power plants have exceeded their designed service life. This increases the risk of crack initiation and propagation, especially in the context of structural components operating at high temperatures, under pressure, and in variable loading conditions. Therefore, ensuring their safe and predictable continued operation is crucial. The topic undertaken in this PhD thesis is therefore entirely appropriate and timely.

The research methods used included experimental studies of mechanical properties, numerical simulations, as well as observation of fracture surfaces and analysis of the materials' microstructure and the changes occurring within it. The relationship between the material's microstructure and its mechanical properties was also investigated. In my opinion, this allows the thesis to be classified under the discipline of materials engineering.

The PhD thesis has a total volume of 163 pages in A4 format. It is divided into seven chapters, which along with the bibliography, are written on 145 pages. These are preceded by a table of contents, lists of tables and figures, a list of symbols, and an abstract in three languages. An appendix with a list of the PhD candidate's co-authored publications and conference presentations is included at the end.

In the **first chapter**, an introduction to the thesis topic, as well as the genesis and motivations for the research, are presented. This is followed by a statement of the main aim, specific objectives, and the scope of the thesis. A synthetic description of the contents of the individual chapters is also included. No research hypothesis or hypotheses were formulated.

Chapter two provides a review of the state of the art in the subject and scope of the thesis. It covers fundamental information on the field of fracture mechanics, modern research methods and standard recommendations concerning the fracture resistance of materials, as well as the types of steel used in thermal power engineering.

The subsequent chapters present the PhD candidate's original research. They constitute the most extensive part of the thesis, covering 93 pages. **Chapter three** describes the results of fracture resistance tests on G17CrMoV5-10 cast steel and 14MoV6-3 steel. The test specimens were manufactured from fragments of a valve and a straight pipeline, which were parts of a steam turbine unit decommissioned after more than 100,000 hours of operation. A mechanical extensometer was used to measure crack opening. Finite Element Method (FEM) calculations were also performed using Abaqus software, along with observations of fractures and microstructure using optical microscopy.

Chapter four presents the results of crack tests on 14MoV6-3 steel specimens loaded in mixed mode I/III. The material was tested in its as-received condition, without any history of exploitation, creep, or aging. To observe crack propagation, a Digital Image Correlation (DIC) system was used. Crack growth was also monitored using the Direct Current Potential Drop (DCPD) method. A FEM model was applied to determine the value of the J-integral. Additionally, fracture analysis was conducted using SEM microscopy.

The research described in **chapter five** concerned 14MoV6-3 steel subjected to high-temperature creep to replicate the material's operating conditions. The crack mouth opening displacement (CMOD) was measured using two mechanical extensometers. The DCPD method was also used again. Following the mechanical tests, the fracture surfaces and side surfaces of the specimens were observed.

In the research presented in **chapter six**, the influence of high-temperature creep and isothermal aging on the fracture of 14MoV6-3 steel was compared. The DIC method was used again to measure specimen deformation during the mechanical tests. The effect of creep and aging on the material's structure was examined by analyzing metallographic samples and fracture surfaces. Additionally, Thermo-Calc software was used to simulate phase transformations and the formation of precipitates.

Chapter seven presents an overall summary of the research results, a discussion, and concise conclusions. It also includes proposals for directions for further research.

The list of references contains 183 entries, although due to numerous errors in the citations, which are discussed in detail below, it is difficult to assess whether all of the listed sources were actually used in the thesis. The vast majority of the literature entries are from the last 10–20 years.

2. Critical and debatable remarks

Reading the text of the thesis raises certain comments and questions, which are likely to be largely subjective in nature. They may serve as a contribution to the discussion during the public defense of the thesis.

2.1. General comments

The thesis is very poorly prepared from an editorial and typesetting perspective. In some parts, it gives the impression of being developed without due care. The text contains a very large number of basic spelling and punctuation errors. There are errors in the spelling of names, for example, "poisons ratio" instead of Poisson's ratio, "Boroski" instead of Boroński, "Gabra" instead of Graba, etc. There are instances of capitalized words in the middle of sentences, inconsistent paragraph styles (e.g., line spacing), font types (even within a single word!), exact same sentences repeated in different places, tables split across two pages without repeating the header and a note about continuation, and incomplete sentences.

Equations, variables, and symbols for mathematical quantities are almost entirely formatted incorrectly and chaotically, which significantly hinders the reading of the thesis. In technical and scientific literature, a fairly consistent typographical rule applies to mathematical formulas. Standards like the ISO 80000 series clearly indicate that variables and symbols for physical quantities should be written in italics, while defined functions, operators, and physical unit symbols should be in roman (upright) font. This also applies to subscripts and superscripts, which in the thesis are essentially written in a random manner. For example, on page 12, the stress concentration factor symbol is written as K_t , Kt and K_t . In many cases, the reader has to guess whether a notation such as $b_0\sigma_y$ should be interpreted as written, or if the PhD candidate meant $b_0\sigma_y$. What is puzzling in the context of these shortcomings is that some parts of the thesis contain mathematical formulas written entirely correctly, for example, (2.9) and (2.10). Modern text editors or systems like LaTeX make it relatively easy to manage even extensive text, and errors in such a number as found in this PhD thesis should not be present.

The issue of correct and consistent formatting and quality also applies to the photos and figures included in the thesis. If a figure consists of several parts, they are often not properly labeled or numbered and are not aligned with each other. The figures are also not uniformly aligned with the pages. There are instances of deformed figures due to a disturbance in the proportions between their height and width. Some figures appear to be low-quality photocopies, or even photos of handwritten sketches. The text in the figures is also a problem. In scientific works, it is generally accepted that the font size and style should be the same as the paragraph text or at least have a uniform style. However, in the thesis under review, there is a large mosaic of text styles in the figures. The errors and flaws listed above not only negatively affect the aesthetics of the thesis but also make some of the figures difficult to read. I believe that a PhD candidate writing a thesis in the field of engineering and technical sciences should be more proficient in the use of graphic software, including CAD software.

Numerous errors also concern the bibliography and the references to its elements within the thesis text. It is a common rule that in the case of multi-author publications, the name of the first author is listed with the note "et al." and the number of the entry in the references list is subsequently provided. However, in the citations included in the thesis text, the names of authors listed later in the source entry sometimes appear. A more serious shortcoming, however, is that in numerous cases, the authors' names cited in the text do not match the corresponding entry in the bibliography. This raises doubts as to whether these and other citations are correct. Similar

to text and graphics editing, numerous reference managers are now available that help in organizing and editing the references list.

A second general remark, which is likely debatable, concerns the way the PhD candidate's research is presented in chapters three through six of the thesis. Each of these chapters is a separate part and is divided into subchapters titled "Materials and Methods," "Results," "Discussion," and "Summary and Conclusions." This leads to unnecessary repetition of certain content, such as the description of research methods and test stands. In my opinion, including a separate discussion of results, summaries, and conclusions in each chapter has led to a lack of more general, overarching conclusions drawn from all the research conducted.

2.2. Detailed remarks and questions

- 1) In Figure 1, parts a) and b) are not labeled.
- 2) The sentence "With, and along with relaxation result in a complex history of operation." on page 2 is incomplete.
- 3) In the sentence "Fractures initiate and grow during this this long complex history of operations." on page 2, the word "fractures" should be replaced with "cracks." The first refers to the complete separation of a component parts, such as a specimen, which is the final state. The second refers to partial damage.
- 4) The text "Some data are available from laboratory tests at normal or elevated temperature. Unfortunately, basic tests are uni-axial, whereas in real boilers it is always multi-axial. Fracture toughness measured by standards defines materials properties more closely than that of components, where the fracture occurs from multi-axial stress fields." is repeated within a short interval on pages 2 and 3.
- 5) Figure 2 and the explanation of the individual creep stages should be placed earlier, before these terms are used in the text.
- 6) In the sentence "In December 2020, more than of Poland's electricity was generated from fossil raw resources, (...)" on page 4, quantitative information on the share of energy generated from fossil fuels is missing. More than... ?
- 7) Figure 3 is distorted due to improper proportions between its height and width.
- 8) On page 6, a sentence in the first person appears: "(...) my research findings (...)".
- 9) The sentence "Unlike toughness, there is no notch and loading are slow." on page 11 is incomprehensible.

- 10) On page 12, the symbol K_I appears (incorrectly written in an upright font), but the meaning of the subscript is not explained. Only a few pages later the information is provided about the three modes of crack loading: I, II, and III.
- 11) On page 13, it is stated that fracture resistance tests are usually conducted based on the recommendations of ISO and ASTM standards. I believe it would be worthwhile to list these standards here. Furthermore, in later sections, the PhD candidate also refers to BS standards.
- 12) I believe that when discussing R-curves, it would be beneficial to include schematic diagrams to supplement the description.
- 13) Figure 6 is of low quality.
- 14) The two following sentences: "Developing a testing technique that includes specimen design, resistance curve analysis, and fracture toughness determination is highly suggested. SINTAP (1999) and BS7910 are fracture mechanics-based procedures for assessing structural integrity. They use a two-criterion failure diagram (FAD) to evaluate the interaction between fracture failure and plastic collapse." do not fit the context of the sub-chapter discussing crack loading modes.
- 15) In the sub-chapter "Advancements in specimens configurations," it would be beneficial to include figures illustrating the types of specimens discussed.
- 16) In the sentence "B.P. Pherson investigated the current fracture toughness test procedure to see if there is a simpler, less complicated way to obtain the J_{IC} value from a fracture toughness specimen test recorded." on page 21, a citation is missing.
- 17) The sentence "Two methods are considered: (i) estimating J and CTOD from plastic work, and (ii) estimating CTOD from the rotational factor of plastic." appears to be incomplete.
- 18) "The findings presented here are like those described in a previous study by Kirk and Dodds [51] (...)". Entry [51] in the bibliography lists different author names.
- 19) "The ASTM E1820 [53] procedure determines δ_{TC} based on crack mouth displacement data (...)". Entry [53] in the bibliography lists a different ASTM standard.
- 20) "Kowalski et al. [21] investigated the effect (...)". Entry [21] in the bibliography lists a different author name.
- 21) "M. Graba [24] investigated the influence of in-plane geometric (...)". Entry [24] in the bibliography lists a different author name.

- 22) In the sentence "J. Kowalski investigated the effect of specimen geometry on the CTOD value for VL-E36 shipbuilding steel experimentally and numerically." on page 23, a citation is missing.
- 23) In the sentence "According to Ž. Božić et. al the stages in fatigue crack growth can be represented by the schematic diagram shown below in Figure 9." on page 23, a citation is missing.
- 24) The sentence "Using two video cameras is intended to enable 3D analyses or to using two video cameras to enable 3D analyses or improve the accuracy of 2D analyses." should be rephrased due to the repetition.
- 25) The sentences "Toughness measurements from high-constraint specimens are typically conservative. Leading to unnecessarily high material selection and pipeline design costs." are doubled on pages 26 and 27.
- 26) Figures 10 and 11 appear to be photos or scans of handwritten sketches. They should be redrawn using appropriate software.
- 27) What does the PhD candidate mean by "the everyday hoop stresses" (page 29)?
- 28) The term "the maximum primary stresses" should be replaced with "the maximum principal stress".
- 29) The elements listed after the colon in the sentence "However, some typical mechanical properties are:" on page 31 should be bulleted.
- 30) The sentence "If the thermal efficiency of power plants can be increased, fuel Conserves fuel and reduces pollution [93]." should be rephrased for clarity.
- 31) Should the sentence "Table 5 and show a comparison of their composition and creep properties respectively." be "Table 5 and 6"?
- 32) The summary formulas for chemical compounds should be written with more care, for example, SO₂, instead of S_o2. Similarly, temperature is written in the thesis as 1100 C, 5⁰C, 1 °C, etc.
- 33) "Vargars-Arista et, al [100] carried out the ageing of weld metal at 250 +/- 5⁰C using a Carbolite resistance oven with a digital controller." Entry [100] in the bibliography lists different author names.
- 34) "Byun et, al [101] used four large muffle furnaces (MTI Co. Model KSL-1200XL) to thermally age the CASS materials over an extended period." Entry [101] in the bibliography lists different author names.

- 35) In the literature review, for example, in the sub-chapters "Ageing oxidation resistance" or "Artificial accelerated ageing of specimen at elevated temperature," there are paragraphs describing research conducted by other researchers, listing materials and methods, but with no information about the results and conclusions. Such a citation adds little to the review of the state of the art.
- 36) The summary presented in sub-chapter 2.4 compensates to some extent for the errors and shortcomings mentioned earlier and the chaotic style of presenting information in the part of the thesis concerning the literature review.
- 37) Figure 17 is a copy of a graphic available on the Wikipedia website at https://en.wikipedia.org/wiki/File:Fracture_Toughness_Thickness_Dependence.svg (accessed August 20, 2025) without a provided reference.
- 38) At the end of the introduction to chapter 3, the PhD candidate states that most of the research results presented in this chapter come from a multi-author research paper listed in the bibliography under entry [10], which the PhD candidate co-authored with his supervisors, among others. In fact, chapter 3 is an almost exact copy of the text and figures from the paper. This raises doubts about the PhD candidate's independent work, as the said article has four authors. The PhD candidate is not the first author, and usually, the authors of scientific articles are listed in an order corresponding to their contribution to the work. Furthermore, at the end of the article, there is a statement about the contribution of individual authors. It shows that the PhD candidate only independently carried out the task of "Data curation." During the public defense, the PhD candidate should clearly and in detail present his contribution to the research and the processing of the results. Additionally, I believe it is good practice in such cases to re-draft the text from scratch.
- 39) The thesis states that the tests presented in chapter 3 were conducted using an extensometer with a 10 mm gauge length, while article [10] indicates it was 5 mm. What is the reason for this difference?
- 40) In the sub-chapter titled "Numerical modeling," it is stated that an FEM model was created to estimate fracture resistance by calculating the J-integral value. It is then mentioned that another FEM model was created to obtain an alternative solution. Please clarify how exactly these two numerical models differed and in what sense an alternative solution was obtained.

- 41) According to the PhD candidate's knowledge, under real operating conditions, do cracks in components like the one shown in Figure 18 appear in the radial, axial, circumferential, or perhaps in all of these directions?
- 42) The sentence "A coarse mesh of was used for the rest of the model to reduce computational cost." on page 46 seems to be incomplete. It should be supplemented after the word "of."
- 43) "The fracture toughness, K_Q , is calculated using the following Equations (3.1) and (3.2) (provided in the standards [53])". The standard listed in bibliography entry [53] concerns the tensile testing of metals.
- 44) Comparing Figure 26 and Table 11, it can be assumed that the values for P_{max} and P_Q were swapped for specimens 2 and 3 in the case of specimens made from the pipe.
- 45) In Table 11, the quantity K_Q has an annotation ($K_Q \neq K_{IC}$), but in Table 12, there is no such annotation. Please provide an explanation.
- 46) It seems that the sentence "Table 13 reports K_{IC}^{REF} calculated for different applied loads, P , for AT specimens on the valve and pipe specimens." on page 50 should be K_{IC}^{FEM} . Please clarify.
- 47) Please explain whether standard functions of the Abaqus software were used to determine the values presented in Table 13, or if it required additional calculations by the PhD candidate.
- 48) In my opinion the full-view photos of fractures, such as the one presented in Figure 33, should be taken using a scanning electron microscope (SEM). This allows for a much better depth of field and contrast.
- 49) "Yan et al. [135] implemented an automated polariscope and three-dimensional photoelasticity to calculate the mode III SIF of 14 mm thick cast blocks of epoxy resin (MY750)." Entry [135] in the bibliography lists different author names.
- 50) There is no reference to Figure 36 in the thesis text.
- 51) Did the use of the DCPD method require the measurement system to be calibrated? If so, what is the calibration procedure?
- 52) There is no reference to Table 20 in the thesis text.
- 53) On page 69, it is written that "This gap accounts for the plastic zone size, which had been previously calculated for each crack length." How was the size of the plastic zone determined?

- 54) In the sub-chapter "Numerical simulations" on page 70, it is stated that an FEM model with an elastoplastic material model was created. Please provide information on what material model was used and how the material parameters for this model were determined.
- 55) In the sentence "In this regard, the $\phi=45^\circ$ notch specimen exhibits a rising R curve while for the straight notch specimens, the R curves are flat." on page 72, it is stated that the R-curves for specimens with a 0° inclined notch are flat. However, Figure 46 shows that the δ_5 values increase with Δa . What did the PhD candidate mean by this?
- 56) In the lower parts of Figures 50 a) and c), where there are no voids characteristic for a ductile fracture and the fracture has a brittle character, are there fragments of stage I of crack growth visible?
- 57) In the "Plastic zone size" sub-chapter on page 77, it is stated that the size of the plastic zone around the crack tip was calculated based on Irwin's formula. Since an FEM model with an elastoplastic material model was created, was the plastic zone size calculated analytically and numerically compared?
- 58) The English word "rupture" is relatively often misspelled as "rapture."
- 59) Similarly to chapter 3, the introduction to chapter 5 also states that the main part of the research results presented in it was published in the multi-author article [56]. The PhD candidate's co-authors are the thesis supervisors, which is understandable. However, in this chapter of the thesis, there are also extensive sections of text and figures copied from the article, which raises similar doubts to those I mentioned earlier. During the public defense, the PhD candidate should also, in this case, clearly present what constitutes his own work.
- 60) According to the PhD candidate's knowledge, do structural components of thermal power plants, such as boiler pipes, also undergo ratcheting under real operating conditions?
- 61) On page 92, the PhD candidate states that the yield stress and tensile strength proved to be insensitive to the aging time of the specimens. Based on Figure 57, it can be concluded that the material's ductility changed. Is this fact irrelevant to fracture resistance?
- 62) Figures 64 and 65 should be swapped in order.
- 63) The first paragraph on page 109 is an exact repetition of the content from page 84. This repetition is unnecessary.
- 64) Figure 73 is redundant because it is a copy of Figure 38.

- 65) On page 155, it is stated that the creep rate significantly increased after 140 hours of the test duration. However, Figure 75 suggests it was closer to 120 hours. I ask the PhD candidate to comment on this.
- 66) Strain is sometimes expressed in the thesis in percentages and sometimes as a dimensionless quantity. In my opinion, the notation should be standardized.
- 67) Figure 76 has low resolution and entries in the legend that are meaningless to the reader. Explanations should appear in the figure caption or in the paragraph text.
- 68) The label "TY" in the legend of Figure 77 a) does not appear in Table 36.
- 69) The order of authors in entry [73] is different from the one in the article.

3. Assessment of the thesis

The topic of the thesis, its objectives, and its scope are scientifically relevant and have significant practical importance. The provided review of the state of the art, despite the previously mentioned comments, is relatively extensive and based on well-chosen literature published in recent years. In conducting the research and analyzing the results, the PhD candidate demonstrated a sound and confident command of the latest knowledge in the thesis field. I assess that the PhD thesis presented for review demonstrates the candidate's general theoretical knowledge to an appropriate degree. However, the formal aspect of the thesis is disappointing, suggesting certain deficiencies in the PhD candidate's proficiency with IT tools.

Based on my reading of the thesis, I find that the PhD candidate has demonstrated the ability to conduct scientific work independently, although as I mentioned in the specific comments, I believe that certain issues regarding the independence of the research conducted should be clarified during the public defense. The presented experimental studies were correctly planned and prepared within the context of the work's topic and objectives. Appropriate research tools were used. The PhD candidate also used suitable research equipment to a degree and extent corresponding to similar works currently being carried out by other researchers. He was able to adapt the methodology and research tools to the specifics of the experiments. The research results were properly analyzed and summarized with consistent and logical conclusions. It is worth to stress out that potential directions for further research were also formulated.

The PhD thesis presents an original solution to the research problem, which was to determine the effect of long-term operational conditions on the fracture resistance of heat-resistant steels used in thermal power engineering. Based on an extensive research program, interesting and

original results and conclusions were obtained. In my opinion, the initial objectives were achieved to an appropriate degree. Furthermore, some of the results presented in the thesis have been published in international research journals with good bibliometric parameters, which indicates that they have been positively evaluated by editorial reviewers.

4. Concluding remark

In formulating my final conclusion, I express the opinion that the PhD thesis by Mr. Bernard Kiptoo Kipsang, MSc, titled "Assessment of Fracture Development in Thick-Walled Elements of Power Boilers after Long-Time Operation" which is the subject of this review, meets the requirements set out in the Act of July 20, 2018, Law on Higher Education and Science (as amended), and I request that it be admitted to public defense.

dr hab. inż. Łukasz Pejkowski, prof. PBŚ

/podpis odręczny/

*wyłączenie jawności w zakresie danych osobowych oraz ochrony prywatności osoby fizycznej na podstawie art. 5 ust. 2 ustawy z dnia 6 września 2001 r. o dostępie do informacji publicznej (tj. Dz.U. z 2016 r., poz. 1764)