Course information – period 1, 2020

Fatigue and Fracture – TME 260

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1 Administrative information

The course corresponds to 7.5 credit points and is mainly targeted towards students at the Master's Programmes

- ▹ Applied Mechanics (MPAME)
- ▹ Advanced Engineering Materials (MPAEM)
- ▹ Naval Architecture (MPNAV)

1.1 Examination

The written examination takes place
2020-10-27 at 08.30 at the Johanneberg campus or on-line (depending on the pandemic situation).

Additional examination are planned 2021–01-05 at 8.30 and in August 2021.

A passed written examination and passed assignments gives 7.5 credit points (hec).

The maximum number of points at the exam are 50 and limits for the different grades are:

- ▹ 20–29 points result in grade 3
- ▹ 30–39 points result in grade 4
- ▹ 40–50 points result in grade 5

The written examination consists of theoretical and problem solving questions (in some tasks these are mixed). For the entire exam, the course material listed in section 1.3 is allowed. This course material may contain notes, cross-references *etc.* Solved examples are however not allowed. Additional material (with the exception of mathematical tables, dictionaries *etc*) are not allowed. This includes slides and lecture notes.

All calculators are allowed, but the memory should be cleared.

1.2 Teachers

The course is given by the Department of Applied Mechanics. Teachers in the course are:

- Prof ANDERS EKBERG[1], 031-772 3480, Anders.Ekberg@chalmers.se
- Prof LENNART JOSEFSON, 031-772 1507, Lennart.Josefson@chalmers.se
- Mr MICHELE MAGLIO, 031-772 1510, Michele.Maglio@chalmers.se
- Assoc Prof JAKOB HEIDBRINK, Gothenburg University, Jakob.Heidbrink@law.gu.se
- Prof JOHAN AHLSTRÖM, Chalmers Materials Technology, Johan.Ahlstrom@chalmers.se
- Mr JAN-ANDERS LINDHULT, Volvo Cars, jan-anders.lindhult.2@volvocars.com

1.3 Literature

D DOWLING N E, KAMPE S L, KRAL M L (2019) **Mechanical behavior of materials**, 5th edition. *Pearson*, USA, 968 pp.

- Repetitions
  - Introduction to material failure – 1.2, 1.3, 1.5
  - Multiaxial states of stress – ch.6 (esp. 6.2,2, 6.3.1, 6.4.2, 6.5), ch.7 (esp. 7.4, 7.5, 7.6.4, 7.7, 7.9)
  - Plasticity – 13.1–13.3, 13.5 (conceptually)
- Introductions to topics covered more in-depth in additional material
  - Anisotropy and composites – 5.4
  - Welds and connections – 10.8–10.9
  - Non-linear fracture mechanics – 8.9, 11.9
- Stress based fatigue analysis – ch.9 (not 9.8), 10.1–10.7, 10.10, Appendix A
- Strain based fatigue analysis – ch.15 (not 15.4, 15.5 as overview), Appendix A
- Fracture mechanics and crack growth: ch.8, ch.11 (not 11.4.2), Appendix A
- Fatigue and fracture testing – ch.3, ch.4
- Statistics in fatigue design – Appendix B

EPFM EKBERG A & ANDERSSON H. (2019) **Non-linear fracture mechanics – A brief overview**. Report 2016:01 edition 2.3. *Department of Applied Mechanics, Chalmers University of Technology*, Gothenburg, Sweden (available for download)

[1] Examiner

MF EKBERG A. (2020) **Multiaxial fatigue**, Report 2012:01 edition 5.6. *Department of Applied Mechanics, Chalmers University of Technology*, Gothenburg, Sweden (available for download)

IIW Extract from **Design recommendations for welded components**, IIW Document XIII-2151r3-07, International Institute of Welding (available for download)

CCP EKBERG A & JOSEFSON B L (2020) **Fatigue of composites, ceramics and polymers**, *Mechanics and Maritime Sciences, Chalmers University of Technology* (available for download)

Note that IIW is a design code and not a text book. Consider the use of this code as training in interpreting and using design codes in engineering.

1.4 Changes since last year

- New edition of the text book with reading instructions and recommended homework revised accordingly.
- The course will be given (mainly) on-line due to the on-going pandemic.

2 Schedule

The allocated lecture time for the course is

Mondays 13^{15}–15^{00} (lecture) and 15^{15}–17^{00} (computer assignments – MT0, MT9 and MT13 booked for those who need access to computers).

Thursdays 08^{00}–11^{45} (lecture)

Fridays 15^{15} –17^{00} (lecture)

Lectures will[2] be streamed. They start at the starting time indicated above, but may not use the entire allocated time. Remaining time is available for consultations related to examples, assignments etc.

Video recordings of the lectures are planned to be available on-line (without editing) on Canvas, but may spread to the public. Thus, if you have any questions that you prefer not to be public, please ask these after the lecture.

Additional shorter videos focused on specific topics may be uploaded to the Canvas course homepage and will then be announced via the Canvas announcement function.

Support for the assignments will be given on-line. Depending on how the pandemic related regulations evolve, support may be provided also in the computer labs.

The detailed schedule is as follows. In case of modifications, this PM will be updated accordingly.

[2] Note that all information is based on the current pandemic situation. As the situation evolves there may be new guidelines and the course will adapt to these.

Week 1: 2020-08-31 – 2020-09-04

D	L	Content	Teacher
M	L1	Load analysis. Introduction to stress-based fatigue analysis (D:9.9, D:9.1–9.7)	Anders Ekberg
M	A1	Assignment 1: Stress based fatigue analysis	Michele Maglio, Anders Ekberg
T	L2	Overview of failure phenomena. Stress-based fatigue analysis (Slides. D:1, D:9.1–9.7, 10.1–10.7)	Anders Ekberg
T	L3	Stress-based fatigue analysis of notched members (D:10.1–10.7, 10.10, Appendix A)	Anders Ekberg
F	L4	Damage accumulation (D:10.1–10.7, 9.9)	Anders Ekberg

Week 2: 2020-09-07 – 2020-09-11

D	L	Content	Teacher
M	L5	Linear elastic fracture mechanics (D:8)	Anders Ekberg
M	A2	Assignment 1	Michele Maglio, Anders Ekberg
T	L6	Fatigue crack growth analysis (D:11.1–11.4)	Anders Ekberg
T	L7	Fatigue crack growth analysis (D:11.4–11.11)	Anders Ekberg
F	L8	Plastic deformation overview (D: 13.1–13.3, 13.5, slides)	Anders Ekberg

Week 3: 2020-09-14 – 2020-09-18

D	L	Content	Teacher
M	L9	Effects of residual stresses. (9.6.4–9.6.6, 10.8.4, 10.8.5, 10.9.1–10.9.2)	Lennart Josefson
M	A3	Assignment 2: Fatigue crack growth – digital twin)	Michele Maglio, Anders Ekberg
T	L10	Design codes for welds (IIW)	Lennart Josefson
T	L11	Fatigue and FE-analysis (IIW)	Lennart Josefson
F	L12	Strain-based fatigue analysis (D:15.1–15.3)	Anders Ekberg

Week 4: 2020-09-21 – 2020-09-25

D	L	Content	Teacher
M	L13	Strain-based fatigue analysis (D:15.1–15.3)	Anders Ekberg
M	A4	Assignment 3: FE-analyses	Michele Maglio, Lennart Josefson
T	L14	No lecture	–
T	L15	Multiaxial states of stress (D: 6, 7 + MF)	
F	L16	Multiaxial fatigue (MF)	Anders Ekberg

Week 5: 2020-09-28 – 2020-10-02

D	L	Content	Teacher
M	L17	Multiaxial fatigue (MF)	Anders Ekberg
M	A5	Assignment 3: FE-analyses	Michele Maglio, Lennart Josefson
T	L18	No lecture	–
T	L19	Fatigue testing demo + lecture (D:3, 4 + slides)	Johan Ahlström
F	L20	Multiaxial fatigue applications (MF + slides)	Anders Ekberg

Week 6: 2020-10-05 – 2020-10-09

D	L	Content	Teacher
M	L21	Limits of linear elastic fracture mechanics (D: 8.9, 11.9, EPFM)	Anders Ekberg
M	A6	Assignment 4: Multiaxial fatigue	Michele Maglio, Anders Ekberg
T	L22	Non-linear fracture mechanics (EPFM)	Anders Ekberg
T	L23	Failures – legal issues (slides)	Jakob Heidbrink
F	L24	Reserved for re-exams – no lecture	–

Week 7: 2020-10-12 – 2020-10-16

D	L	Content	Teacher
M	L25	Fatigue of composites, polymers and ceramics (CCP)	Anders Ekberg
M	A7	Assignment 4	Michele Maglio, Anders Ekberg
T	L26	Statistics in fatigue analysis (D: App. B)	Anders Ekberg
T	L27	Repetition and problem solving regarding codes, welds and FE-analyses	Lennart Josefson
F	L28	Repetition	Anders Ekberg

Week 8: 2020-10-19 – 2020-10-23

D	L	Content	Teacher
M	L29	Fatigue analysis in industry	Jan-Anders Lindhult
M	A8	Assignment 4	Michele Maglio, Anders Ekberg
T	L30	– if required –	Anders Ekberg
T	L31	– if required –	Anders Ekberg
F	L32	– if required –	Anders Ekberg

Week 9 (w44)

Exam 2020-10-27, 8.30–13.30 at the Johanneberg campus.

Recommended homework

Some recommended exercises in Dowling's book. Select (and extend) depending on your needs. Also have a look on old exams to get a better picture of the scope of the course.

Chapter 9 (do not use eqs 9.6 and 9.7, but instead methods in ch.10 for fatigue life predictions) 9.18, <u>9.19,</u> 9.34, <u>9.45</u>, 9.46, 9.47

Chapter 10 10.4, 10.5, 10.6, 10.10, 10.16, 10.17, 10.32, 10.33, 10.35

Chapter 8 8.6, 8.7, 8.8, 8.9, 8.10, 8.11, 8.28, 8.29, 8.36, 8.43, 8.52 (8.51 ed.4)

Chapter 11 11.1, 11.9, 11.31, 11.32, 11.33, 11.38, 11.39, 11.48, 11.50, 11.52

Chapter 15 15.9a, 15.10a-c, 15.29, 15.31, 15.49 (presume elastic–perfectly plastic or power law and use Neuber)

3 Compulsory assignments

There are four compulsory assignments in the course. The assignments contain computer programming parts. Languages used are optional but MATLAB is recommended (and supported). In one assignment the FE software ANSYS Workbench is planned to be used.

The assignments may be solved in groups of two students and handed in group-wise. Deadlines for handing in the assignments are given below. In exceptional cases, hand-in can be delayed following an agreement with a supervisor. Still, written reports for all assignment must be submitted before the final written exam.

The assignments aim at exemplifying the theory studied. They do not give any credit points for the exam. For this reason, programming skeletons are provided and fairly extensive support can be given. Note however that *programming* support on assignments will only be given if skeletons are followed. Support regarding *fatigue and algorithms* is of course always provided.

1. **Stress based fatigue design**
   Responsible teacher: AE
   Supervisor: MM, AE
   Available 2020-08-31. Time to finish and hand over to supervisor: 2020-09-14
2. **Fatigue crack growth – example of a digital twin**
   Responsible teacher: AE
   Supervisor: MM, AE
   Available 2020-09-14. Time to finish and hand over to supervisor: 2020-09-28
3. **Design codes for welded structures: FE-based analyses**
   Responsible teacher: LJ
   Supervisor: MM, LJ
   Available 2020-09-21. Time to finish and hand over to supervisor: 2020-10-12
4. **Multiaxial fatigue**
   Responsible teacher: AE
   Supervisor: MM, AE
   Available 2020-10-05. Time to finish and hand over to supervisor: 2020-10-26

The assignment report should include:

- **One** page with

- **Course name and code** (i e Fatigue & Fracture – TME 260) and **number of the assignment**
- Your **name(s)** and **Chalmers code(s)** or personal number(s)
- **Date of submission**
- **Brief** summary of **task** and **main results**

In the industry this is the *Executive summary* that you will present to the commissioner.

▹ On the remaining pages you present **detailed and structured calculations**

In the industry this is your *technical documentation* aimed at the specialists at the commissioner's technical department.

▹ Don't forget **pagination** and state the **total number of pages** of the report on each page.

4 Course content

The course covers **fatigue and fracture mechanics**. In particular three approaches for fatigue design of structures and components are studied: The **stress based approach** where the global mechanical response is elastic. Here the influence of stress raisers needs particular consideration. In the **strain based approach** an even more detailed analysis is adopted to account for localised yielding at stress raisers during cyclic loading. Finally, the **fracture mechanics approach** explicitly analyses the growth of cracks using methods of **fracture mechanics**. The limitations of using **linear elastic fracture mechanics** studying crack growth and final fracture are discussed and an introduction to **non-linear fracture mechanics** is given.

For all these approaches, methods to evaluate fatigue life that can be expected under various operational load conditions (including **irregular load histories** and **multi-axial loading**) are presented and motivated.

In the industry the use of **codes for fatigue design** is common. In this course, such approaches are demonstrated for the case of **welded joints**. Further, **fatigue design in conjunction with FE-analyses** of stresses and strains in a component is given special attention.

In addition to the main focus on **metallic materials**, the course also provides an overview of fatigue of materials such as **composites**, **polymers** and **ceramics**. In particular challenges regarding submitting such materials to fatigue loading, and available means of predictions are discussed.

In this context it can be noted that especially fatigue is a phenomenon highly affected by **statistical uncertainties** (in load, strength, geometry etc). The course will provide an overview of this topic and also provide some insight into **how fatigue design is carried out in**

the industry. Related to this topic is the **introduction to fatigue testing** including a **lab visit**.

Finally, cases where the design has not prevented operational failures will be discussed. This includes discussions on reasons for some failures, as well as insight into how **failure investigations** are carried out and how **allocation of legal responsibilities** can be made.

The presented theory is applied to case studies in **four assignments**.

4.1 Aim of the course

The student should understand mechanisms behind fracture and fatigue failures and be able to design and analyse structures and components subjected to various types of fatigue loading while accounting for various types of influencing parameters. Further, the student should be able to choose suitable fatigue design criteria depending on type of loading, design and application. The student should also be able to account for statistical uncertainties and have a knowledge of fatigue testing, failure investigations and legal issues related to failures.

4.2 Learning outcomes

After completion of this course, the student should be able to

- ▹ master concepts of fracture mechanics, and fracture
- ▹ understand and describe the physical background to initiation and growth of fatigue cracks, especially in metals.
- ▹ identify and quantify fatigue loading situations for engineering components and structures, and in particular be able to formulate algorithms needed to analyse fatigue life under irregular load histories
- ▹ choose and apply different (stress based, strain based and fracture mechanics based) approaches to fatigue design of components and structures made of metallic materials, and also understand the limitations of these approaches
- ▹ understand how approaches for fatigue design can be employed also for other materials such as composite materials and polymers and which limitations such adaptions have
- ▹ estimate material parameters needed for fatigue life predictions and be aware of testing possibilities and challenges
- ▹ master design against fatigue under multi-axial loading situations
- ▹ carry out fatigue design according to European design codes by hand and in conjunction with FE analyses, in particular for assemblies with a focus on welded joints
- ▹ understand how statistical uncertainties influence the reliability of predictions
- ▹ have a knowledge of failure investigations and allocation of responsibilities

4.3 Prerequisites

The student should have basic knowledge in Solid Mechanics (Strength of Materials), the Finite Element Method and Mathematics. Knowledge in Continuum Mechanics is preferable but not necessary.

We hope you will find the course to be worth the efforts you invest in it!

Gothenburg, August 2020

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