THESIS REVIEWER'S REPORT

I. IDENTIFICATION DATA

Thesis title:	**Quality Evaluation of Finite Element Models with Applications on Concrete Structures**
Author's name:	**Aneta Bulíčková**
Type of thesis:	master
Faculty/Institute:	Faculty of Civil Engineering (FCE)
Department:	Department of Concrete and Masonry Structures
Thesis reviewer:	Dr. Burkhard Bornemann
Reviewer's department:	RIB Engineering GmbH, Vaihinger Str. 151, D-70567 Stuttgart, Germany

II. EVALUATION OF INDIVIDUAL CRITERIA

Assignment — **extraordinarily challenging**

How demanding was the assigned project?

RIB TRIMAS is a proprietary structural design software for 3D structures which has been developed since the 90s. RIB TRIMAS has been developed towards a graphically interactive application offering an integrated user-experience for finite element analysis and design as well as pre- and post-processing. The meshing process is an integral part of the finite element analysis and is performed automatically without much influence of the user. The underlying, rather robust, mesh algorithm was implemented a very long time ago. Occasionally, the question arises about the quality of the generated mesh. Now, the idea was to quantify the mesh quality based on computation of plates. This would ideally lead to a criterion to highlight mesh regions, which have a potentially adverse impact on the results. To capture the relation of element shapes to low quality results, the plate mesh examples must be created with artificially distorted elements. Due to the focus on effortless automatic mesh generation, the mesh cannot be easily artificially distorted using the graphical interface. Moreover, RIB TRIMAS as well as its currently developed successor RIB iTWO structure fem lack support to visualise element shape metrics, since the post-processing is based on a result database.

Fulfilment of assignment — **fulfilled with minor objections**

How well does the thesis fulfil the assigned task? Have the primary goals been achieved? Which assigned tasks have been incompletely covered, and which parts of the thesis are overextended? Justify your answer.

A criterion to identify element shapes proved difficult and was not achieved. However, the essential steps were all done: Investigation of element shape metrics (Chapter 2 and 3); generation of a mesh file to visualize the element shape metrics with ParaView (Chapter 4); convergence studies of artificially distorted example meshes (Chapter 5). These three parts cover wide-spread areas, i.e. from mathematical/geometrical over programming to parametric studies and all require quite different software applications to deal with. The student was confronted with a multitude of unknown software (cf. p. 54), which were handled well. In Chapter 2 and 3, various element shape metrics are well presented. The student does not sufficiently separate between element shape functions and applied mechanical model. So, the linear triangle is referred to constant strain triangle, which is somewhat misleading. Since it refers to the mechanical wall (also known as membrane, or planar solid mechanics) model discretised with purely displacement-based linear triangles. The programming part (Chapter 4) is possibly too detailed, on the other hand, it shows how thoroughly the object-oriented programming paradigm was understood and how much thought went into the algorithms. It is difficult to create artificially distorted meshes within RIB TRIMAS and iTWO structure fem, in which the elements are particularly misshaped to monitor effects of the various element shape metrics. The plate examples showed to be challenging to gain effects – much to the supervisors' surprise. So, the student also investigated a wall example (Chapter 5.1).

Methodology — **outstanding**

Comment on the correctness of the approach and/or the solution methods.

(A) Element shape metrics (Chapter 2 and 3). The student firstly introduces the shape functions for triangular and quadrilateral reference shapes of linear and quadratic polynomial order. Some characteristics of these shape functions are summarised in Table 2.1 with an eye towards their application to purely displacement-based finite elements for planar solid mechanics. Different element shape metrics are well presented using examples and extremal cases. Notably, figures are employed to study and connect the metrics, i.e. a number, with actual element shapes, i.e. geometry.

(B) MeshEvaluator software (Chapter 4). The MeshEvaluator software was created by the student to convert the mesh from RIB TRIMAS/iTWO structure fem to a VTK file used as input by the ParaView visualiser. The VTK file was also provided with the various element metrics. The MeshEvaluator software was written using the object-oriented paradigm. The object-oriented design of the software was convincingly presented using Unified Modelling Language (UML, e.g. Figure 4.5). The software has a suitable modular design. The element data (Chapter 4.3 and 4.5) is separated from the IO (Reader Chapter 4.4 and Writer Chapter 4.6). Notably, a unit test (Chapter 4.7) was provided to yield reliable software, that is reliable element shape metrics.

Technical level **A - excellent.**

Is the thesis technically sound? How well did the student employ expertise in the field of his/her field of study? Does the student explain clearly what he/she has done?

Most of the thesis deals with the fields of finite element shapes (Chapter 2 and 3) and object-oriented programming (Chapter 4) which are not the core subject of civil engineering. These topics are well presented in a way, which highlights the effort to understand them. Maybe with the exception where finite element shape functions and the applied mechanical model are insufficiently differentiated.

In Chapter 5, a cantilever and a two-way slab are studied, which are closer to typical civil engineering curricula. Here, the student compares the computational results with analytical solutions. The appropriate mechanical Timoshenko beam model is taken in Chapter 5.1; also care was taken to select the support conditions correctly (cf. App. C.1). In Chapter 5.2, the need for a shear-flexible plate model is recognised and discussed (Appendix C.2).

Formal and language level, scope of thesis **A - excellent.**

Are formalisms and notations used properly? Is the thesis organized in a logical way? Is the thesis sufficiently extensive? Is the thesis well-presented? Is the language clear and understandable? Is the English satisfactory?

Yes to every question.

Selection of sources, citation correctness **A - excellent.**

Does the thesis make adequate reference to earlier work on the topic? Was the selection of sources adequate? Is the student's original work clearly distinguished from earlier work in the field? Do the bibliographic citations meet the standards?

The original work by the student is clearly pointed out and references are given. However, as stated elsewhere, finite element shape functions and applied mechanical model are somewhat intermingled. So, at times general statements are not supported by including a reference. These statements are limited to a context and this context is not given. The bibliography is clear, but the reviewer would have preferred a publishing company and place for every listed monograph.

Additional commentary and evaluation (optional)

Comment on the overall quality of the thesis, its novelty and its impact on the field, its strengths and weaknesses, the utility of the solution that is presented, the theoretical/formal level, the student's skillfulness, etc.

The overall quality of the thesis is high. Although the topic is rather wide spread, all these areas were managed. And they were managed well, where the theory was understood. In this case the thesis explains to undertaken steps very cohesive. The thesis has its weaknesses, where some aspects were not entirely understood, like the insufficient separation of finite element shapes and applied mechanical model. However, since the element shape metrics as well as object-oriented programming, which are challenging themselves, were well done, it can be forgiven that the finite element analysis was treated somewhat superficially.

The difficulty to create artificially distorted meshes with RIB TRIMAS/iTWO structure fem was underestimated by the supervisors. Therefore, a mesh quality indicator could not be established. However, the student worked creatively with RIB TRIMAS/iTWO structure fem yielding many meshes to provide an insight into the loss of result quality.

The created MeshEvaluator software tool continues to be useful for further development of the meshing process of RIB iTWO structure fem.

THESIS REVIEWER'S REPORT

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III. OVERALL EVALUATION, QUESTIONS FOR THE PRESENTATION AND DEFENSE OF THE THESIS, SUGGESTED GRADE

Summarize your opinion on the thesis and explain your final grading. Pose questions that should be answered during the presentation and defense of the student's work.

The thesis studies the relation of finite element shapes to the result quality for bending of planar structures as computed by RIB TRIMAS and RIB iTWO structure fem.

The theory behind the linear and quadratic shape functions of triangular and quadrilateral element reference shapes is well presented and interlinked with various element shape metrics. The change of metric with respect to the geometrical shapes is thoroughly investigated using examples and extremal cases. Figures support this nicely.

The aspects of finite element shape function and applied mechanical model is somewhat intermingled. This also affects the so-called locking, that additionally depend on the so-called finite element technique.

The design of the MeshEvaluator software tool, which was newly created by the student, is well documented. The object-oriented software design is convincingly presented. The use of Unified Modelling Language (UML) abstracts object-oriented design from the implementation with the C++ programming language. The design is appropriately modular (and extensible), i.e. Reader and Writer were separated from the element data. In other words, the MeshEvaluator software was carefully and thoughtfully engineered.

The student studies many artificially distorted meshes for a cantilever beam and a two-way slab system. The overall effect of the artificially distorted meshes are investigated using convergence diagrams for, e.g., displacements. To provide a fair comparison, the finite element results are compared to an analytical solution. The discussion of support conditions and mechanical models shows a sound critical engineering mind.

The student overcame many software hurdles while performing her thesis, e.g., ParaView, Microsoft Visual Studio, RIB TRIMAS and RIB iTWO structure fem.

To summarise, I propose a grade for the thesis of **A - excellent.**

Questions:

a) Table 2.1: Which mechanical model is meant by the "Pros" and "Cons"? Or are these statements valid for any planar mechanical model, regardless being an in-plane (wall) or an out-of-plane (plate) problem?
b) When comparing FEA results with an analytical solution, how important is the choice of the analytical mechanical model and applied support conditions?
c) Figure 5.9: Does the relative amount of "unacceptable" (i.e. red elements) relate to the relative deviation from the expected "reference" result?

Date: **21.1.2020**

Signature: Burkhard Bremann