Marcin Kozłowski, PhD, DSc, Assoc. prof.

Silesian University of Technology
Faculty of Civil Engineering
Department of Structural Engineering
Akademicka 5
44-100 Gliwice
Poland

Gliwice, 08.04.2022 r.

# OPPONENT'S REVIEW OF THE DOCTORAL THESIS

| | |
|---|---|
| Candidate: | Eng. Tomáš Hána |
| Title of the doctoral thesis: | Time and temperature dependent shear stiffness of polymeric interlayers and its effect on laminated glass in bending |
| Study programme: | Third-cycle programme |
| Tutor: | Doc. Ing. Martina Eliášova, CSc, Ing. Miroslav Vokáč, PhD |
| Opponent: | Marcin Kozłowski, PhD, DSc, Assoc. prof.<br>Email: marcin.kozlowski@polsl.pl |

## Formal basis and the subject of the review

The review has been prepared at the request of Prof. Dr. Ing. Bořek Patzák - Vice-Dean for Science and Research at the Faculty of Civil Engineering at Czech Technical University in Prague, expressed in a letter issued on March 7, 2022.

The subject of the review is the doctoral dissertation of Eng. Tomáš Hána entitled "Time and temperature dependent shear stiffness of polymeric interlayers and its effect on laminated glass in bending". This work was prepared at the Department of Steel and Timber structures at the Faculty of Civil Engineering at Czech Technical University in Prague. The thesis was prepared under the supervision of Doc. Ing. Martina Eliášova, CSc and Ing. Miroslav Vokáč, PhD.

The reviewed dissertation contains 243 pages in a single volume. It includes 186 pages of the thesis, three pages summarizing the list of author´s publications related to this thesis and 54 pages of appendixes.

## Topicality of the doctoral thesis theme

The topic of the dissertation chosen by the author concerns laminated glass as a novel load-bearing product widely used in contemporary architecture. A particular focus has been paid to the performance of out of plane loaded laminated glass under various temperatures and loads of different duration. It was investigated by an extensive experimental campaign aimed at describing time- and temperature-depended stiffness characteristics of selected polymeric interlayers and their effect on the mechanical response of laminated glass. Analytical and numerical studies supported the investigation.

In the light of the lack of European standards and a common design approach, the research topic undertaken by the author is relevant and actual. In particular, it is worth emphasizing that, in addition to the well-known PVB interlayer, the author examined two types of EVA foil, which in recent years have significantly increased their share in the laminated glass market and were the subject of limited research. In the above context, the author clearly defined two goals of the thesis: description of time and temperature-dependent shear stiffness of selected polymeric interlayers and the effect of shear stiffness of selected interlayers on the performance of laminated glass panels in out of plane bending.

**Formal layout of the doctoral thesis and the level of language used**

The content of the thesis is contained in fourteen chapters, supplemented with the list of the cited literature (80 items) and seven appendixes.

Chapter 1 (a half-page) provides a brief introduction to the subject of the thesis. In Chapter 2 (44 pages), the author presents state of the art regarding glass material, laminated glass and interlayers. The chapter provides the basic material properties of glass and discusses the differences among its types. Subsequently, the author highlights the issues concerning the performance of laminated glass and the time- and temperature-dependency of different polymeric interlayers. The chapter also covers an overview of experimental testing and mechanical models for polymeric interlayers. Chapter 3 (two pages) introduces the scope and goals of the thesis. In Chapter 4 (one page), the author presents the thesis's general layout and stages. Chapter 5 (six pages) contains detailed information regarding the technical data of selected interlayers and manufacturing details of small- and large-scale specimens. In Chapter 6 (45 pages), the author presents the results of extensive experimental campaigns. This regards static and dynamic single-lap small-scale shear tests, four-point bending of large-scale specimens with various loading rates and four-point creep of large specimens. Chapter 7 (29 pages) covers the analytical considerations of the thesis. It provides the coefficients of Williams-Landel-Ferry and Maxwell-Weichert models for the selected interlayers and the analytical response of models to various strain rates and temperatures. In Chapter 8 (27 pages), the author reports the results of FE analysis of four-point bending of large samples with a viscoelastic material model. The numerical results are compared with the experimental values. Chapter 9 (9 pages) compares the values of effective thickness of laminated glass calculated with Wölfel-Bennison and Effective Thickness method approaches with the values obtained from FE software. In Chapter 10 (12 pages), the author provides examples of practical calculations of load effects acting on double laminated glass panels according to the EN 16612 standard. Chapter 11 (2 pages) provides conclusions of the thesis. In Chapter 12 (2 pages), the author highlights the achieved outputs for engineering practice. Chapter 13 (2 pages) presents the author's plans for further research. In Chapter 14 (3 pages), the author lists the main outputs of the research in terms of publications in journals.

Although the reviewed thesis has a high formal standard of visual form and content, it presents a too fragmented structure. Chapters 3 and 4 should be combined and moved to the beginning of the thesis. The same applies to Chapters 12 and 13. In addition, Chapter 5 should be merged with Chapter 6 since it is directly related to it.

All used sources are cited correctly. The text is written in clear and understandable English.

## Research methods and procedures

The research methodology involving three components (experimental, analytical and numerical) is presented in Chapters 6, 7 and 8.

The experimental work included static and dynamic single-lap small-scale shear tests, four-point bending of large-scale specimens with various loading rates and four-point creep of large specimens. The research methodology is correct and minutely reported. During testing, various repetitions were applied; however, the number allows for statistical assessment. Figures in Chapter 6 present the average results for the interlayers at various temperatures. It has not been clarified how the curves were generated and what was variation.

The analytical part was aimed at determining coefficients of Maxwell-Weichert model and master curves for the selected interlayers based on the results of the experimental campaign. In addition, the analytical stress-strain relations were verified by the experiments. The presented methodology is clear and correct. However, it would be interesting to perform a comparison of the achieved coefficients of viscoelastic model for the interlayers reported in literature and standards (e.g. NEN 2608). In addition, presenting the details of the optimization scripts in the numerical computing platform would be beneficial and increase the cognitive value of the work.

The numerical campaign involved verification of shear stiffness moduli determined in previous parts. It was done by comparing the numerical results with the results of four-point bending of large-scale specimens loaded monotonically and under constant load. Within the work, two software were used. An engineering program that enables only a linear elastic model for the interlayer; and a complex scientific platform with a linear viscoelastic material model.

The presented methodology is correct and proper. However, an analysis of the model's sensitivity to the initial parameters (e.g. material parameters, geometry, etc.) and size effect would increase the cognitive value of the work. The same applies to the numerical analysis of the single-lap shear test in the light of reported variation of the interlayer thickness in the experimental part of the work.

## Results of the doctoral thesis – dissertant's concerete achievements

The main results of the thesis are presented in Chapter 11. These include a complete description of time- and temperature-dependency of shear moduli of common PVB and EVA polymeric interlayers used in laminated glass components. In addition, it proposes a replacement of the current approach for the determination of effective thickness included in EN 16612 with the Enhanced Effective Thickness method that includes the shape and boundary conditions in an assessment of panels.

The thesis is the first work that comprehensively describes a variety of interlayers used in the glazing industry. It is definitely of great importance for the scientific community and engineering practice.

## Importance for practice and for development within a branch of science

The thesis is of great value in terms of applicability in engineering practice and scientific research. It reports extensive results of the experimental campaign together with strong analytical and numerical background. Particularly relevant to practitioners are the calculation examples shown in Chapter 10 and the outcome of the work – a guide for a practical design of laminated glass balustrade and floor according to DIN 18008. In terms of the scientific research, the thesis provides a detailed mechanical description of interlayers that can be used in research. In addition, in light of the lack of European standards, the thesis has great potential to be implemented in the standardization documents.

## Fulfilment of the doctoral thesis objectives

The thesis objectives described in Chapter 3 have been fulfilled within the presented thesis. The obtained results have a strong potential to be used by scholars in scientific research and by professionals in their engineering practice.

## Final assessment of the doctoral thesis

Summarizing this review, I state that the doctoral thesis prepared by Eng. Tomáš Hána entitled "Time and temperature dependent shear stiffness of polymeric interlayers and its effect on laminated glass in bending" significantly contributes to the area of structural glass. The presented work fulfils the requirements for a doctoral dissertation in this particular area. The author has successfully demonstrated his ability to address the scientific problem and solve it correctly.

Some critical remarks of varying importance have been formulated in the review; however, the work is very valuable. The feedback may be taken into account by the candidate in publications and further research.

After considering the advantages and disadvantages of the reviewed thesis, I consider it original and meets the requirements for a doctoral dissertation. Thus, I recommend it for public defence.

## Questions to the candidate

During the defence, I would like the following questions to be answered:

1. How were the results (e.g. stress curves) for repetitions in the studies averaged? What deviations were observed for these runs?

2. How would you structure the output of the thesis (e.g. in the form of tables, figures) if it was intended to be included in standards and be used by engineers?

3. Most engineering software (used by practitioners) does not cover viscoelastic material models. What would be the procedure to determine Young's modulus of an interlayer for a specific combination of temperature and load duration?

Marcin Kozłowski, PhD, DSc, Assoc. prof.