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Uncertainty caused variability in preliminary structural design of buildings

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ABSTRACT

Many decisions in the everyday work of the structural engineer are taken under the influence of uncertainties. The degree of uncertainty affects the quality and variability of the outcome of the structural design work. The effect of uncertainties related to knowledge and experience of the structural engineer was studied in a round robin investigation. Despite a relatively well defined task, the results varied considerably among the 16 participating Swedish structural engineers that performed this task; a structural check, load takedown and stability calculation for a five storey concrete building. The column load of a specific position differed by a factor of three between lowest and highest suggested value. For the stabilizing forces the values varied even more. The uncertainties connected to the structural engineer were estimated by introducing the term *Engineering Modeling Uncertainty*, divided into a structural model part and a load part. These uncertainties are shown to have a large effect on structural safety. The significant variability in results and the consequence on structural safety of this investigation emphasizes the importance of documentation and communication of all the assumptions made by the structural engineer – even the apparently obvious ones.

1. Introduction

Uncertainty is the inevitable companion of the structural engineer. The exploration of structures not yet erected does and must contain a considerable amount of uncertainty in order to meet the demands of modern architecture and the general expectations on a good building. It is one of the structural engineers' most important undertakings to manage these uncertainties and despite their existence be able to make the right decisions in the evolution of the new building.

Uncertainties not recognized or not treated with sufficient respect risk to lead to errors committed, and ultimately to the collapse of buildings. In order to avoid such collapses, different checking systems have been developed. In the building industry of Sweden, this is normally regulated by individual self-checking of calculations complemented with checking of drawings by the responsible engineer or manager of the project. External checking or inspection is normally not performed for buildings in Sweden. Even if this checking is performed, errors slip through which can cause failure of structures.

In recent years attention has been drawn to a number of structural failures in Sweden that may be connected to the work of the structural engineer. In 2008 the false-work of a bridge over Älandsfjärden collapsed when the concrete was poured, killing two construction workers. In the same year the web of a slender steel beam over a road in Kista buckled when the slabs it was designed to carry were mounted, this also with lethal consequences. In 2012, during the time for the present study, a three storey building under construction collapsed in Ystad [1] – fortunately during the night causing nothing but material damage. Studies by Frühwald et al. on 127 collapsed timber structures indicate that approximately 53% of the structural failures in this study are due to incorrect design [2]. Studies performed for instance by Matousek et al. [3] and Melchers et al. [4] suggest, with similar figures, that design errors provide a significant contribution to the number of structural failures.

These failures have occurred despite systems regulating quality control and checking. Maybe the systems are not good enough to ensure a sufficient level of quality? According to Nowak and Carr [5] most errors are "detected and corrected through various controls, including self checking by the error-maker". The efficiency of checking, as a function of checking time and error size, is described by Melchers [6] and suggests that, given unlimited time and regardless of error size, only approximately 85% of the

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errors committed will be detected. Another suggestion is that the skill and knowledge of the engineers may be insufficient. Ellingwood [7] discusses the combination of those and claims that calculation blunders normally are detected by checking while more fundamental errors such as "fundamental misconceptions regarding structural behavior and lack of attention to boundary or support conditions" are "the most serious source of design error". In Sweden self-checking is the most common type when it comes to checking of calculations for buildings. It is reasonable to believe that this system does not detect errors connected to lack of fundamental knowledge of structural behavior and thus structural safety, in this sense, will depend on visual control of drawings, normally performed by a colleague or manager.

The discussion of errors often requires the existence of a correct solution, at least when discussed at an academic level. Under the influence of uncertainty of a real project, this discussion must instead assume the correct answer to be a range of acceptable solutions. Previous investigations performed by Stewart and Melchers in Australia [6,8], and by Bürge and Schneider in Switzerland [9] all displays a rather large range and variability in the results of engineering calculations when performed by professional structural engineers. A conservative approximation may be considered an error from a mathematical point of view but is often the only passable way forward for the engineer in practice. This report is therefore dedicated to the often subjective grey area between the uncertainties covered by design codes and the indisputable errors. This is an area, difficult to master, in which the engineer often is forced to perform his or her craft.

2. Round robin test of preliminary structural design

The methodology to estimate the variability in the results of different structural engineers that participated in this investigation is based on the principles of round robin testing. A round robin test is performed independently several times by different laboratories, or as in this case, by different structural engineers. Based on a given set of input data, the method enables comparison of the output and how it is affected by different choices of complementary data, code interpretation and analysis models chosen by the individual participants.

The investigation consisted of two primary parts – a quantitative data collection part (the focus of this article) and a qualitative part for validation of the results. In the first part the participants were subjected to an engineering task similar to the tasks normally performed by the engineer in his or her daily craft. In order to achieve representative results for this part, the setup was carefully designed to resemble real tasks for the engineers. This means that the task was presented similarly to a real case and performed under both, time and economical pressure. Accordingly, some additional input was required to be assumed by the participants. Calculation reports were not required as current Swedish legislation does not demand regulatory control of calculations. Instead the results and questions connected to how they were achieved were followed up in the qualitative part of the investigation, which enabled a more precise and nuanced understanding of assumptions and errors committed.

2.1. Participants

The participants of this investigation were all experienced engineers working in medium to big structural engineering offices in Sweden. A total of 16 engineers, all with MSc-degree, participated in the investigation with an average experience of 12 years as practicing engineers. Prior to the investigation the manager of each office was contacted and asked to select a suitable participant given the following requirements; minimum five years of experience, experience from concrete, steel and timber structures and finally experience from early stage preliminary design. For a real task the procedure and considerations would be manned in a similar way. To further enhance the impression of a real task, and to ensure a high return rate, the companies employing the participating engineers were paid for up to eight hours of work per task, which was assessed to be sufficient for this type of task at the actual stage of the design process. The correctness of this assessment was monitored in the qualitative part of the investigation.

2.2. The studied building

The first part of the task was primarily a load takedown calculation for a multistory residential building with public spaces on ground floor. The building has a concrete structure with columns and three shear walls on the ground floor oriented in the building's transverse direction. The structure above ground floor consists of transverse concrete walls, which in turn support the concrete slabs, see Fig. 1.

The engineers were provided with a set of architectural drawings typical for this stage in the building process; plan and section drawings, façade drawings and three rendered 3D pictures (a part of this material is presented in Figs. 1 and 2). The following information was given in text:

- New building with 40 student apartments and restaurant at ground floor.
- Located by the sea in Malmö, Sweden.
- Pile foundations is required.
- Walls between apartments: 200 mm semi precast walls with a total thickness of 200 mm with hollow core that is cast in situ.
- Slabs: lattice girder floor consisting of a 50 mm precast deck which is poured on top to a total thickness of 220 mm.
- Top floor for installations constructed by lightweight insulated wooden panels (walls and roof).

2.3. The task

The participants were asked to answer the following questions for the submitted material:

1. Check if the concrete dimensions given by the provided material is sufficient.
2. Suggest dimensions for the concrete columns on ground floor (precast concrete).
3. Calculate the loads from the structure acting on the pile foundations.
    - For stabilizing units also provide moments and shear forces.

The task was designed to provide a geometrically uniform and simple building but with a number of challenges in the analysis. It was intended to be reasonably demanding for both, the engineer deciding to use hand calculations as well as for those choosing to use for instance finite element software. It also was supposed to provide the engineers with a number of possible paths to follow for the analysis.

3. Results

The engineers chose very different ways of presenting their results. The extent of the results ranged from a few values written down in an e-mail or on a plan drawing to full calculation reports. In order to create a consistent set of data, each participant was asked during the data evaluation if the result somehow was