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Recommendations for structural assessment of RC slabs using the finite element method

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ABSTRACT: To mitigate environmental impact and societal costs, there is a need to extend the lifetime of existing transportation infrastructure. Research has shown that many structures, such as bridges, have a substantial inherent load-carrying capacity that is often not fully utilized. In the research presented, it was shown how non-linear numerical analysis can be used to show higher performance and longer lifetime than with conventional engineering methods. Comprehensive recommendations for use in engineering practice have been developed for the structural assessment of reinforced concrete slabs using the finite element method. A multi-level structural assessment strategy was developed to provide a framework for successively improved and more advanced analysis. For the more advanced levels, non-linear FE analysis is used, adopting a global safety format and incorporating the effects of deterioration. With such analyses, the structural behaviour can be more accurately described and higher, yet conservative load-carrying capacities can generally be demonstrated.

1 INTRODUCTION

To reduce environmental impact and carbon emissions, and to optimise the utilization of the society´s resources, it is of outermost importance that the huge investments in transportation infrastructure are well managed. It is imperative that existing structures must be utilized during their entire lifetime with respect to function and safety, and their capacity must be fully used to meet higher demands from the transportation industry. When assessing existing structures, many of these shows insufficient load-carrying capacity, often accompanied by uncertainties regarding the structural behaviour. However, tests on real structures as well as experience with advanced assessment methods shows that existing structures often have substantially higher intrinsic capacity and a more complex structural response than shown with conventional assessment methods, see e.g. Bagge at al. (2018).

For design and assessment of reinforced concrete structures, simplified analysis methods and code provisions are commonly used. For structural analysis, the linear finite element (FE) method is common. However, for the assessment of existing structures, a greater effort with more advanced methods for structural analysis is often motivated. Research as well as experience from engineering practice has shown that non-linear FE analysis provides great possibilities of achieving a better understanding of the structural response, and have demonstrated the potential to reveal higher load-carrying capacity, see e.g. Shu et al. (2018) and Bagge et al. (2019).

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Today, non-linear FE analysis is a standard method within research, but it is still sparsely used in engineering practice. This is partly because the method is more demanding, but also because it includes many uncertainties regarding in-data, modelling choices and result interpretation. There has also been concerns regarding the safety format since the partial factor method, normally used in design, may be questioned in the context of non-linear analyses.

The goal of the work presented was to develop detailed recommendations for how non-linear FE analysis can be utilized for structural assessment of reinforced concrete structures in engineering practice. The work focused on reinforced concrete (RC) slabs, but the principles, strategies and many of the methods developed are generally applicable. The objectives of the work were to (1) develop a methodology for incorporating non-linear FE analysis in successively improved structural assessment, (2) develop analysis methods for different levels of assessment of RC slabs and (3) through examples demonstrate and show the potential of the recommended approach. The research methods used included literature studies, laboratory tests, analytical and numerical analyses as well as parameter studies. In addition, the methodology and recommendations presented are founded in the authors' own long experience of non-linear analysis and structural assessment, within research as well as in engineering practice.

2 A MULTI-LEVEL ASSESSMENT STRATEGY

The assessment strategy is based on a stepwise approach where the structural assessment is made with successively more sophisticated methods for evaluation, see e.g. Sustainable Bridges (2007). These can consist of more advanced structural analysis methods, improved knowledge of the structure and its condition, and with safety formats suitable for the analysis methods employed. In Figure 1, a principal flow diagram for the assessment process is shown.

A Multi-Level Assessment Strategy was proposed in Plos et al. (2017) to facilitate enhanced assessment through successively improved structural analysis and resistance evaluation. The framework also provided a structured approach to the use of non-linear FE analysis for structural assessment of RC slabs. Five different assessment levels were proposed, see Figure 2. The assessment starts with traditional simplified analysis methods (Level I), followed by the currently dominating linear FE analysis method (Level II). The higher levels (Levels III – V) involves non-linear FE analysis on different levels of detailing.

A non-linear FE analysis simulates the response of the structure. It resembles the structural behaviour under successively increased loads, possibly up to and beyond the failure of the structure. This means that the load-carrying capacity can be evaluated from the non-linear analysis directly, provided it is sufficiently detailed to reflect the governing failure mode. If all possible failure modes of interest are not reflected in the analysis, the related action effects from the analysis must instead be compared to local resistances for these failure modes, similarly as in standard design methods. This is the case for some of the failure modes at Levels III and IV, see Figure 2.

While the common resistance models from e.g. Eurocode 2 (2004) are used at Levels I and II, higher Level-of-Approximation resistance models from Model Code 2010, fib (2013), are proposed for Levels III and IV. The five assessment levels are briefly described below.

- Level I: Simplified analysis methods: 2D linear beam or frame analysis, tabulated solutions or plasticity-based analysis like the strip method or the yield line method.
- Level II: 3D linear FE analysis: Generally shell element analysis. Modelling and redistribution of stress concentrations according to e.g. Pacoste et al. (2012).
- Level III: 3D non-linear shell FE analysis: Non-linear material properties of concrete and reinforcement, including concrete cracking and crushing and reinforcement yielding, Perfect reinforcement-concrete bond is assumed. Bending failures are reflected in the global analysis, while shear type and anchorage failures are checked separately.
- Level IV: 3D non-linear FE analysis with continuum elements: Here also shear type failures, including punching, can be reflected with sufficiently dense element mesh.
- Level V: 3D non-linear FE analysis with continuum elements including reinforcement-concrete bond-slip: With even finer mesh resolution also anchorage failure and realistic crack distribution can be reflected. No major failure modes are checked separately.

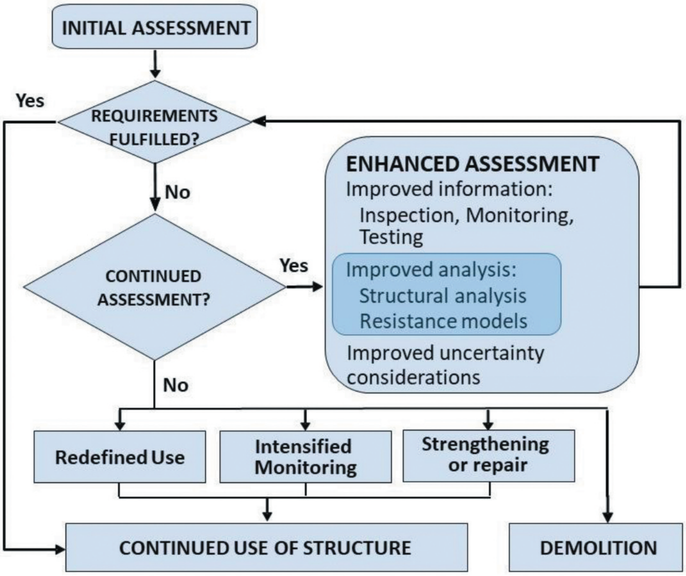

Figure 1. Flow diagram for successively improved structural assessment. Based on Plos et al. (2021).

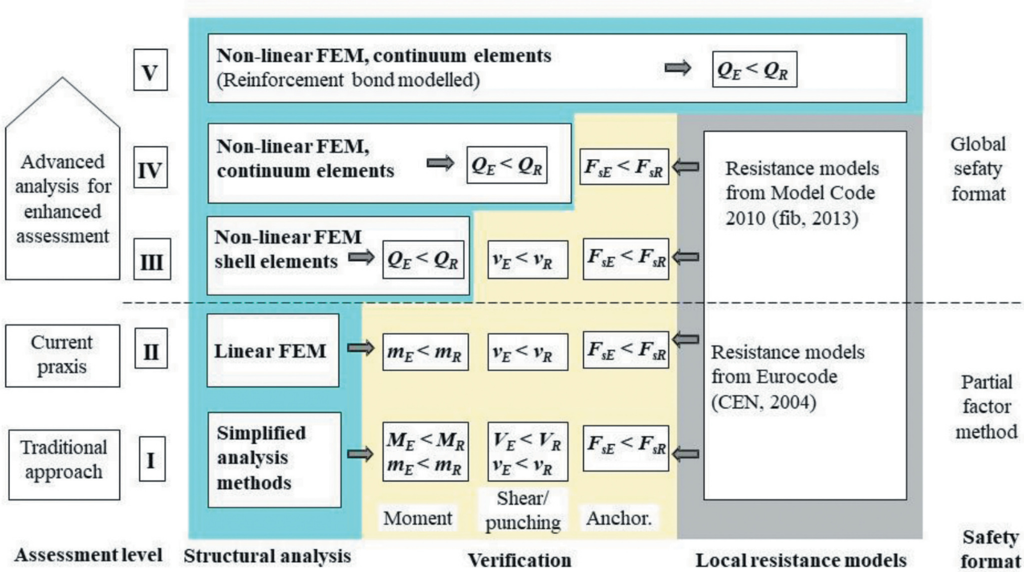

Figure 2. Illustration of the Multi-Level Assessment Strategy for RC slabs. From Plos et al. (2017, 2021).

It must be emphasized that in practical terms, it is necessary to start the assessment with analyses on the lower load levels, i.e. Levels I or II. With such an analysis, the structure can be assessed for a great number of load combinations and load positions. As the analysis progresses to non-linear stages, the response becomes history-dependent and load effects from different loads cannot be combined. Instead, a separate non-linear analysis must be made for each combination of loads studied. Since it is comparably more time consuming and computationally demanding to do a non-linear analysis, such analyses are recommended for evaluating a limited number of critical load combinations, previously identified on lower assessment levels.

For analysis with simplified methods or linear FE analysis according to current standards (Levels I & II), the partial factor method is used to meet the safety demands. However, a non-linear FE analysis simulates the response of a structure during successive loading to failure for a specific load combination. It can be seen as a virtual testing of the existing structure as a whole and is by its nature always a global type of assessment. Consequently, global safety factor methods are recommended for use in combination with non-linear finite analyses for assessment on Levels III, IV and V. In Plos et al. (2021), detailed recommendations are given for their application.

3 NON-LINEAR FE ANALYSIS

For analysis on different levels of detailing, structural analysis methods were developed and proven feasible for the assessment of existing concrete slabs, see Shu et al. (2015, 2016, 2017). The analysis methods were verified through comparison with laboratory tests. Sensitivity studies of modelling choice were made for slabs subjected to bending as well as shear type failures. Detailed recommendations for application of the analysis methods on the different assessment levels are given in Plos et al. (2021). In particular, detailed recommendations regarding modelling, analysis and evaluation for non-linear FEM is given for analysis with shell elements (Level III) and continuum elements (Level IV and V). How the global safety format and the resistance models from Model Code 2010, fib (2013), can be applied on each level is described, in combination with the non-linear analyses.

In addition to the detailed recommendations for RC slabs, general recommendations for modelling and analysis of concrete structures with non-linear FEM are given in Plos et al. (2021) . Many of the challenges and questions that a practicing structural engineer is facing when performing this kind of analysis are addressed and recommendations are given regarding modelling choices and application of the methods. Detailed guidelines are provided regarding determination of material parameters and other in-data for the analyses. Advices are given for quality check and interpretation of analysis results.

The response in a non-linear analysis is history dependent. The order in which the loads are applied may therefore be important. It can influence the response during loading, but also the interpretation of the obtained failure load. Since detailed rules on this are not available in standards or codes, recommendations are given for the load application in non-linear analysis.

When the structure is deteriorated due to, for instance, reinforcement corrosion or frost damage, the structural effect of the deterioration needs to be counted for in the structural analysis or in local resistance models, see e.g. Zandi (2010). For different levels of assessment, recommendations are given in Plos et al. (2021) on how the effect of such deteriorations can be included as a change in material properties, cross-sectional area of the concrete and reinforcement, and bond properties between reinforcement and concrete.

4 EXAMPLES

The feasibility and potential of the assessment strategy and the analysis methods were shown through applications to laboratory tests as well as real structures, see Shu et al. (2015, 2016, 2017, 2018, 2019). In Plos et al. (2021), they are demonstrated in three examples. In two of the examples, concrete slabs previously tested in laboratory by Fall et al. (2014) and Vaz Rodrigues (2007) were studied. In Figure 3, the analyses on different levels are illustrated. The potential to demonstrate higher load-carrying capacity was demonstrated through comparison between test results and analyses on different levels. In the third example, the strategy was demonstrated on an existing bridge with future (hypothetical) deterioration from reinforcement corrosion and frost, including the application of the global safety format. Figure 4 summarises the load-carrying capacities possible to demonstrate through analyses on the different assessment levels. For the slabs tested in laboratory, the load-carrying capacity relates to the measured failure load. For the composite bridge deck slab, it relates to the capacity demonstrated with non-linear FEM on level IV.

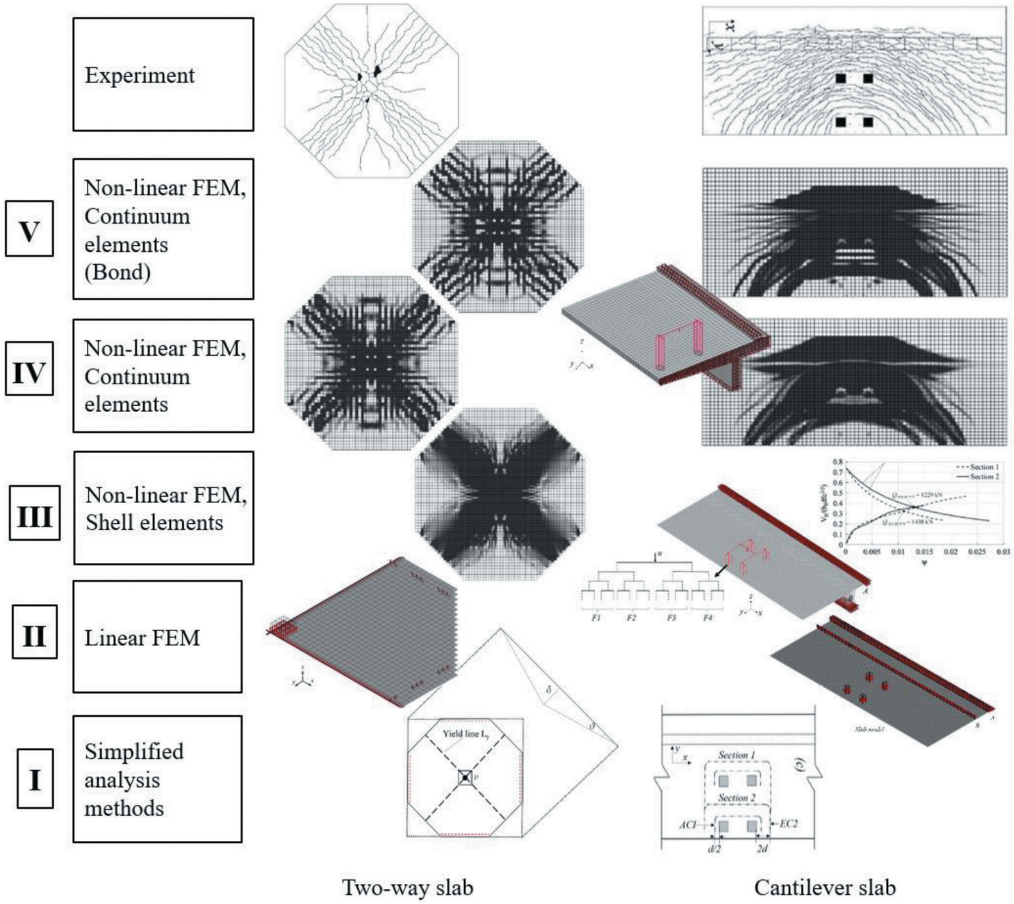

Figure 3. Illustration of analyses on different levels of accuracy, for slabs tested in laboratory. From Plos et al. (2021). Test performed by Fall et al. (2014) and Vaz Rodrigues (2007).

5 CONCLUSIONS

To facilitate the use of advanced analysis methods in engineering practice, recommendations were developed for structural assessment of RC slabs, Plos et al. (2021). A methodology for successively improved assessment, and analysis methods for different levels of assessment were developed. The methods recommended are intended for use in engineering practice and follows current standards and established handbooks such as CEN (2004) and fib (2013). They are intended to give conservative estimates of the load-carrying capacity, fulfilling the required safety level. While the recommendations are formulated for RC slabs, the underlying principles are universal and many of the recommendations are relevant also for other type of structures. Plos et al. (2021) provides a clear framework for structural assessment of RC structures, gives detailed recommendations for analyses on different levels of detailing and includes examples showing the application.

In the examples, it was demonstrated how more accurate assessment can be made using non-linear FE analysis for cases where simplified analysis cannot demonstrate sufficient load-carrying capacity. A substantially higher part of the intrinsic capacity of the structure could be demonstrated using more advanced analyses.

Non-linear analysis with shell elements in combination with resistance models from Model Code 2010, fib (2013), (Level III) are judged to be useful for practical engineering work. They are more demanding than traditional analysis methods but are powerful when a higher load-

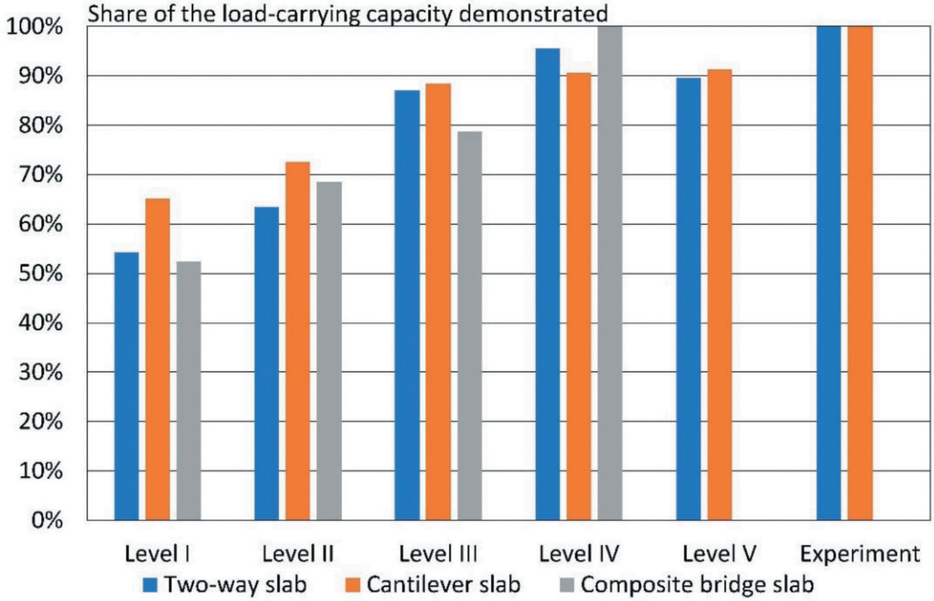

Figure 4. Demonstrated load-carrying capacity with assessment on different levels of accuracy, for the examples in Plos et al. (2021).

carrying capacity needs to be demonstrated. It was shown through examples that assessment with such an analysis can result in 15% to 35% higher capacity compared to assessment according to current praxis using linear analysis.

Non-linear analysis with continuum elements (Level IV and V) can be very helpful to provide a better understanding of the structural behaviour. However, this kind of analysis is considerably more demanding. Furthermore, there are still doubts regarding the modelling uncertainty which, in practice, makes it difficult to prove additional capacity with such analyses.

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REFERENCES

Bagge, N., Popescu, C., & Elfgren, L. 2018: Failure tests on concrete bridges: Have we learnt the lessons? *Structure and Infrastructure Engineering*, 14(3): 292–319.

Bagge, N., Plos, M. & Popescu, C. 2019: A multi-level strategy for successively improved structural analysis of existing concrete bridges: examination using a prestressed concrete bridge tested to failure *Structure and Infrastructure Engineering*, 15(1): 27–53.

CEN 2004. *EN 1992-1-1 Eurocode 2: Design of concrete structures - part 1-1*. Brussels, CEN.

Fall, D., Shu, J., Rempling, R., Lundgren, K. & Zandi, K. 2014. Two-way slabs: Experimental investigation of load redistributions in steel fibre reinforced concrete. *Engineering Structures*, 80:61–74.

fib 2013. *Model Code for Concrete Structures 2010*. Lausanne: fib.

Plos, M., Shu, J., Zandi, K. & Lundgren, K. 2017. A multi-level structural assessment strategy for reinforced concrete bridge deck slabs. *Structure and Infrastructure Engineering*, 13(2): 223–241.

Plos M., Johansson M., Zandi K. & Shu J. 2021: *Recommendations for Assessment of Reinforced Concrete Slabs: Enhanced structural analysis with the finite element method*. Göteborg, Chalmers Univ. of Tech. https://research.chalmers.se/publication/523655/file/523655_Fulltext.pdf

Pacoste, C., Plos, M., & Johansson, M. 2012. *Recommendations for finite element analysis for the design of reinforced concrete slabs*. Stockholm: KTH Royal Inst. of Tech.

Shu, J., Fall, D., Plos, M., Zandi, K., Lundgren, K. 2015. Development of modelling strategies for two-way RC slabs. *Engineering Structures*, 101: 439–449.

Shu, J., Plos, M., Johansson, M., Zandi, K., Nilenius, F. 2016. Prediction of punching behaviour of RC slabs using continuum non-linear FE analysis. *Engineering Structures*, Vol. 200 art. no. 109666.

Shu, J., Belletti, B.; Muttoni, A., Scolari, M., Plos, M. 2017: Internal force distribution in RC slabs subjected to punching shear. *Engineering Structures*, 153: 766–781

Shu, J., Bagge, N., Plos, M., Johansson, M., Yang, Y., Zandi, K. 2018: Shear Capacity of a RC Bridge Deck Slab: Comparison between Multilevel Assessment and Field Test. *J. Struct. Eng.*. Vol. 144 (7)

Shu, J., Honfi, D., Plos, M., Zandi, K., Magnusson, J. 2019: Shear Capacity of a RC Bridge Deck Slab: Comparison between Multilevel Assessment and Field Test. *J. Struct. Eng*. Vol. 144 (7)

Sustainable Bridges 2007: *Non-Linear Analysis and Remaining Fatigue Life of Reinforced Concrete Bridges*. Prepared by Sustainable Bridges - a project within EU FP6.

Vaz Rodrigues, R. 2007. *Shear strength of reinforced concrete bridge deck slabs*. Lausanne. PhD Thesis, École Polytechnique Fédérale de Lausanne,

Zandi K. 2010: *Structural Behaviour of Deteriorated Concrete Structures*. Göteborg, Ph.D. Thesis, Chalmers Univ. of Tech.