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Nonlinear structural analysis as an assessment tool for existing concrete structures

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Abstract

This paper gives an overview what the impact of nonlinear analysis can have on the remaining capacity of an existing concrete structure. Today and in the past a concrete structure is designed on the level of a linear analysis. The layout of the reinforcement is mostly designed on a cross sectional base, where quasi nonlinear behaviour on the cross-section is included. Also in the past some phenomena, like shear force behaviour, were neglected in design recommendations. The shift to a full nonlinear analysis is a great step, so after more than 20 years of improvement of concrete material models and improvement of CPU, in 2007 a decision has been made to setup a workshop around shear force behaviour related to nonlinear analysis. The result of this workshop was to setup a Nonlinear guideline for concrete structures for the framework of the re-examination of existing concrete structures. In 2010 the Model Code 2010 was published with safety formats to extend the checks of concrete structures, re-examinated by nonlinear analysis. The first draft of Nonlinear guideline was published in 2012, reason to setup a second workshop to get a better dissemination under the concrete analysis.

Keywords: nonlinear analysis, concrete, assessment, re-examination, guideline

1 Introduction

1.1 General

The Dutch Recommendation for the design of concrete structures built before 1976 didn't have any shear force check. At that time the shear force phenomena was neglected as an aspect in the design process of concrete structures.

In 1976 the first version of checking the shear force phenomena was published and all recommendation after 1976 got improvements. Since 2012 the Netherlands are using the Eurocode set as the design tools for all different materials and if not available yet, there are still Dutch CUR recommendations available. Between 1975 and 1985 also the research aspects on concrete mechanics side was started, not only in the numerical part, but also in the experimental part. Finite element analysis had to prove their value in the design. Similar to that, also the nonlinear analysis has to prove their value. Not directly in the design of concrete structures but also on the level of re-examination of concrete structures. This value is also illustrated in the updated version of the Model Code 1990[…] to Model Code 2010[…]. Safety formats are introduced for the necessary checks of nonlinear analysis results or setting up the process of nonlinear analysis on the input models. Of course there are still some improvements needed in this field, but nevertheless the first results show an extension of the remaining capacity of existing concrete structures versus the results of the usual linear analysis. Discussions and workshops around those topics improve the use of this 'new' method, the first step to accept this approach is already made.

1.2 Assessment

Assessment is not only a matter of re-examination of structures but also a matter of archiving design documents, modifications to the structure and doing periodically inspections. Archiving design documents can divided into drawings, material properties, retrofitting drawings and re-examinations of the structure. The use of the structure can be changed in the lifetime of the structure, shifting from a structure with 2 lanes and a hard shoulder to a structure with 3 lanes is rather common in the Netherlands. Widening an existing structure is also a common process. Not every structure is dimensioned on these changes, so archiving these changes in a right way is very important for the future. The remaining design lifetime is for a lot of structure not yet reached, so even if there is no extended overall lifetime this aspect is still important. Based on these archives a re-examination of the structure can be started. A tool to give the chance on a proper re-examination is already presented in 2013[..]. To get a first indication of the reliability of a concrete structure is also presented in 2013[..]. Based on this Excel or MathCad Quick Scan procedure the decision can be made to setup a FE re-examination based on 1D or 2D elements. A so-called beam or slab model can give a more proper reliable indication of the structural behavior. If these models aren't enough then 3D solid models can be used, where the shift from liner to nonlinear can be made as well. When there is a certain level of damage to the structure, the archived inspections reports can give an answer to the degradation of the structure, so this archive part is completing the archiving focus. The last ten years a lot of work has been done to digitalize the design drawings of the structures and make them accessible to the end users. Meanwhile there are many developments to come to an extension of the Model Code 2010 related to existing structures. To make the work done sofar an automated framework is setup to examine already concrete structure with draft recommendations. When there are changes in the recommendation only the basic QuickScan tool has to be changed and within some hours all structures in the whole highway network get its new reliability indication. The basic input of structures is stored in a database, which is coupled to the earlier mentioned QuickScan tools. QuickScan tools are setup for culverts, slabs and pre-fabricated beams. This means that in the future almost 70-80% of our concrete structures in the Netherlands have a reliability indication. Structures with a low reliability are going to the program of retrofitting or replacement of structures. To validate those QuickScan tools analytical calculations and FE calculations has been made or setup.

2 Workshop 2007

2.1 General

In 2007, an international workshop around the state of art of different analytical approaches and FE codes has been held. The base of this workshop was to show the participants the value of their own implemented FE code on three chosen experiments. Two experiments were selected from the literature and only one experiment was never published. The post-diction of the ultimate limit load was asked and the crack growth behavior. The overall re-examination time for these three experiments was set to three months, starting after the summer in August 2007. The workshop was planned in December 2007 in Rotterdam, the Netherlands. Thirty enthusiastic participants had a very fertile discussion not only about the results but also about the interpretation of the input data given on forehand. The input data given in SI units was based on the description of the characters and symbols of the Model Code 1990, but it seemed to be not uniform enough under the participants.

2.2 Results workshop

Nevertheless the results of the ultimate load were not uniform. These results are given in figure 1.

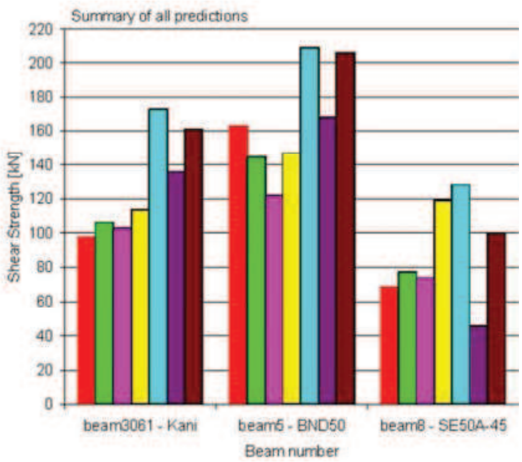

Figure 1. Shear strength of the three simulations by experts

Figure 1 shows that at least that there is a large scatter in the shear strength of all three experiments. The variation on each experiment is also large and probably the third experiment, beam8 called in figure 1, is a so-called edge experiment which is beside the standard recommendation or a very complex experiment. The crack pattern behavior of this third experiment is shown in figure 2.

Figure 2. Crack pattern of the third experiment

Figure 2 shows a crack pattern what is started as bending cracks on the opposite side of the left bottom support or right upper loading point. After the development of the cracks a shear crack is starting on the location where the extra reinforcement is starting over a length of 1 meter. This bream, is rather heavily reinforced, so can be announced in that way as an complex beam configuration which isn't so close connected to or covered by the usual recommendations. The results can also be given in a way that the simulations are safe or unsafe. This can be shown in figure 3.

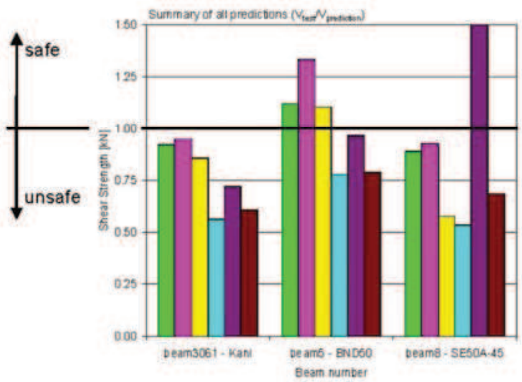

Figure 3. Safe or unsafe presentation of the results

Only 4 of the 18 simulations seemed to be safe and the scatter is in the range of 55% till 150%. This safe index seemed to be very low and looking to the unsafe regime, the most unsafe ratio is 45%, which will not cover the partial safety factor connected to results of the linear analysis. So there more effort has to be put in nonlinear analysis knowledge dissemination.

3 Nonlinear Guideline

3.1 Development

The development of the guideline should not only help the analyst to get a robust calculation scheme but also accurate results. The second option was to make use of a selected number of material models, load models and other FE choices. The setup of the format in which the guideline is written is the same like the Model Code 1990 and later also the Model Code 2010. This means on the right side the main provisions and on the left side comments or explanations of provisions, sketches or simplified rules. Also some indicative numerical values are sometimes given.

3.2 Content Guideline

The content of the Nonlinear Guideline shows not only the technical aspects of a nonlinear analysis but also how to report this type of analysis. Otherwise the checking authority is not able to check the number of results in a restricted time period. The number of preferred material models is already restricted, so with using the provisions of the guideline in that way the description of a structure can be minimized. It is allowed to use not mentioned provisions but then the results should be comparable and that should be proven in that case for that type of structure. The content of the guideline is as follows:

1) Introduction
2) Modelling
    a. Material properties
    b. Constitutive models
    c. Finite element discretization
    d. Prestressing
    e. Existing cracks
    f. Loads
    g. Boundary conditions
3) Analysis
    a. Loading sequence
    b. Load incrementation
    c. Convergence criteria
4) Limit state verifications
    a. SLS
    b. ULS
        i. GRF
        ii. PF
        iii. ECOV
5) Reporting of results
    a. Analysis Input check list
    b. Results check list
    c. Model checks
6) References

This overview of the content shows the common aspects of an analysis, like material models, geometric aspects, boundary conditions and loads. Especially loads and boundary conditions can be coupled to refinements in FE modelling. Usually the boundary condition of a support or a load location in the design process is coupled to a node or point of the FE model. In the re-examination process of existing structures it isa rather useful to look at the impact of the shift from point location to an area location. At htat moment the load isn't anymore a force but a distributed load. To deal with existing cracks is another issue in this field, orthotropic material behavior can help the analyst a little bit further, however a sequence of load over the structure within a nonlinear analysis is recommended but time consuming.

Only the limit state aspects under the ULS verifications might be unusual, but the Model Code 2010 and also the Eurocode 2 gives these new verifications on the ULS load level. There are 3 approaches:

- GRF(Global Resistance Format) approach,
- PF(Partial Format) approach and
- ECOV(Estimation of Coefficient of Variation) approach.

The preference and most accepted approach is the GRF approach. The disadvantage of the PF approach is the addition of the partial factors to the characteristic input values of the material. With this approach the material input values of a re-examination are getting very low, which results not only in a very low ULS level but it is also possible to get another failure phenomena. The ECOV approach takes two nonlinear runs instead of one nonlinear run at the other approaches. However, the ULS result is mostly larger, so there is more remaining capacity belonging to the structure. All these approaches are still under research so these approaches will be modified in the future.

3.3 Validation of the Guideline

After the setup of the guideline the content should be proven. To prove the content of the Nonlinear Guideline for practical usage, simulations of experiments and structures has been made. This work package is divided into 3 parts related to existing concrete structures in engineering practise :

- Reinforced beams
- Prestressed reinforced beams
- Reinforced slabs

When these 3 parts are validated, also structure like box-girder bridges, tunnels, culverts, prefab T beams with intermediate slab panels can be re-examined. Every work package part shows at least 4 simulations, for the slabs this is extended to 5 simulations. A lot of different analysts, Master students, PhD students and university employees fulfill this work package. A final report of all these simulations including some variations will be published in the summer 2015. In that way this type of work is traceable for the future. The results of three prestressed reinforced beams is added to this paper.

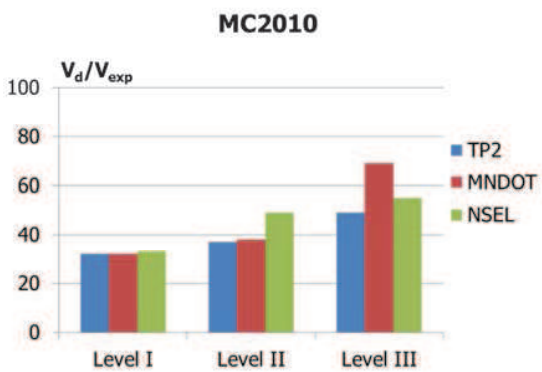

Figure 4. Analytical results checked by the MC2010

The three experiments are coming from:

- TP2: Leonhardt, Koch and al.
- MNDOT: Runzell, Shield and French
- NSEL: Sun, Kuchma

Figure 4 shows in a first stage the results of the analytical re-examinations, checked by the first three levels of Approximations of the Model Code 2010. Figure 4 shows also clearly that the results of the analytical re-examinations come to a ULS level of 70% of the maximum experimental result level. Looking to the loadlevel at level I, belonging to the usual linear analysis partial safety factor approach, the result reaches only to 35% of the experimental result ULS value. The results of the nonlinear analysis are shown in figure 5 for two prestressed beams. Figure 5 shows all three safety formats which are described in the Model Code 2010. The minimum loadlevel at the GSF format counts for 58% of the experimental ULS loadlevel. All other safety formats show a larger ULS loadlevel, so the remaining capacity is increased by this nonlinear analysis simulation of this experiment. The maximum is here 72% of the ULS loadlevel of the experiment by the included model uncertainty of 1.27.

The partial safety (PF) approach shows a small increase of the ULS loadlevel and the ECOV approach shows still more capacity.

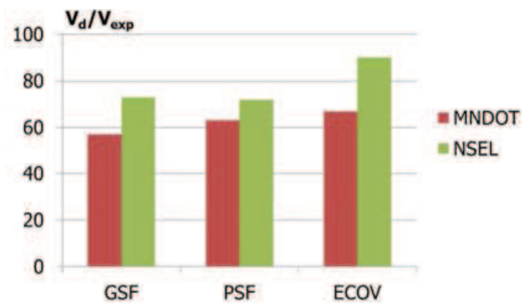

Figure 5. Results of different nonlinear analysis MC2010

Of course there should become also a general safety value for the other approaches by using the nonlinear analysis for re-examination purposes. Not only for the used models but also for the material modelling etc. No doubts about that; this aspect is under research worldwide today.

Another example of using the safety factors at a slab, described in the PhD thesis of Lantsoght[..].

Figure 6. View of one of the Lantsoght slabs with a concentrated load nearby a support line

The slabs have dimensions of 5 by 2.5m, with a thickness of 0.30m. There are 2 support lines, which means that the span of the slab will become 3.6m. The wheelprint simulation has an loadarea of 0.2m by 0.2m.

The finite element model is shown in figure 7.

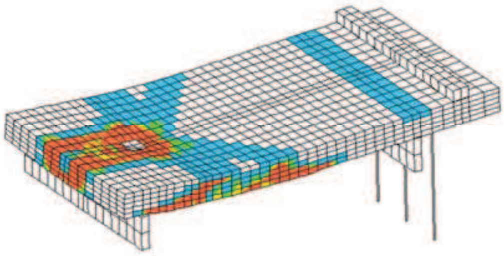

Figure 7. Iso-view of the FE model of the slab

The figure shows the concentrated load on the left side of figure 7. The plotted stresses in the figure are the results on the SLS load level. approach increases the loadlevel a little bit, the GRF nonlinear loadlevel approach increases till almost.

Also for this slab the linear partial safety approach gives a 26% result of the experimental ULS loadlevel. The probabilistic analytical Level III. The 90% of the experimental ULS loadlevel is reached in that way, so the nonlinear procedure of the used FE code looks promising. This effect can be seen also at the other MC2010 approaches.

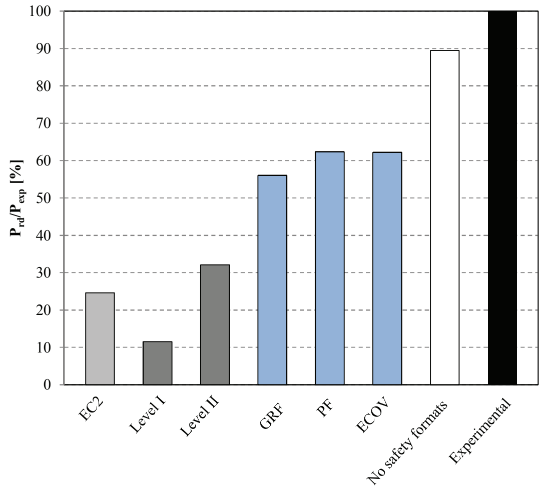

Figure 8. Results different safety formats MC2010

4 Workshop 2014

4.1 General

The nonlinear guideline is setup using 2 FE ccodes, ATENA and DIANA. Both FE codes are coming from the concrete mechanics research environment and are worldwide used by consultants, universities, contractors and governmental authorities. Both FE codes have more modules for other business aspects but the focus here is concrete mechanics. Already in the validation process a lot of members have contributed to a lot of simulations of experiments. In 2014 there was a chance to predict the ULS behaviour of some T-beams, which should be tested later in 2014 at the Delft University of Technology. It was rather unique that there were 4 beams, almost identical in geometry. The important difference was the width of the flange, while there were 2 edge beams and 2 mid beams available coming from a larger test setup. Every beam could be tested on the left and right side of the beam so in total there should come 8 ULS loadlevel values. At the EURO-C concrete mechanics conference in St. Anton Austria, March 2014 this prediction was announced. The participants got the time till September 2014 to submit their results to the prediction organisation. By the total amount of 8 tests, in this case also a distribution could be given afterwards of the ULS loadlevels, which is unique. Already at the announcement there was planned a workshop in November 2014 at the Parma University to compare the results of the different teams and have discussions.

Figure 9. Overview fourT- beams Stevin lab Delft

Also the additional questions could be submitted, important in the case that there were becoming similar answers to get a real winner at the end. These additional questions for the international contest were:

1. Maximum (and minimum) load at failure.
2. Failure mechanism.
3. Cracking pattern at SLS (at 75% of failure load) and ULS.
4. Crack width at SLS (at 75% of failure load).
5. Load-displacement diagram at position of the load.

Looking to the organisation of the first workshop in 2007, all participants who were involved in this workshop were invited to give their opinion about the subject ULS loadlevel. In this workshop the participants are free to submit, are not payed on forehand but could win a cheque of 500 euors.

4.2 Results of the workshop 2014

Forteen teams submitted a prediction of the ULS loadlevel, which was already on forehand a success. Beside that there were 7 countries present and they used in total 6 FE codes. While the workshop was located in Italy participants not related to the teams which had submitted their contribution were coming mostly from Italy. But Spain, Portugal, the Netherlands, Norway and Tsjechie were present too. Regarding the results coming from the experiments, there were only 4 test results available at the time the workshop was held. A delay in the lab was reason for that result, but nevertheless the these results were the source for a discussion after the presentation of the predictions how to proceed with the tests. The first tests showed no real shear failure, but a flange failure by compression. The compression failure shows at the end of course also spalling of concrete of the web. The ducts of the transverse prestressed reinforcement were the origin source of this failure. Filling these ducts with an additional grout concrete could minimize this failure in the extreme situation. On the movies it could be seen that the failure exceeds in a split second.

Every team likes to have a so-called pitch presentation of their contribution. Of course the available 6 minutes is very short but with a pre formatted presentation this was well done by all of the participants. So everybody has kept strictly the available time.

Looking to the results of the prediction of the different teams a better result was given then in 2007. The ULS loadlevel from all 14 teams was between the 68% and the 110%. So the most important conclusion was that a lot of predictions were shifted to the safe side. Even the 110% is for the FE code still acceptable. The range of partial safety factors or uncertainties added to these kind of nonlinear analysis are always above the 1.1 and mostly in the range of 1.25 or even 1.35.

The winner was chosen from a selection of 4 teams, they were in the range of 97% till 103%. Based on the additional results the winner came to the ULS loadlevel of 100.2%.

The discussions at the end of the workshop how to proceed with the other 4 test examples gave reason to the force load closer to the supports. Meanwhile this test work is done and the other T-beams are tested in this proposed way.

The guideline itself got some remarks in extension or other provisions which could be mentioned also as an alternative on the draft version of the guideline. Together with the report of all validation simulation a new version of the nonlinear guideline for beams and slabs will be published around the summer of 2015.

All contributions will be published later on a bulletin format related to the concrete society or a international journal. This will be decided and planned after publishing the new version of the guideline and the belonging validation report.

5 Conclusion

In general it can be concluded that this type of workshop takes time from the participants, but is also very useful to look how every person is dealing with modelling, re-examination of concrete structures and reporting those results. All participants were enthusiastic about the provisions of the guideline and the guidance of this document.

The progress in nonlinear analysis over the period of 2007-2014 has made an important step and the hope is to setup a new workshop with prediction in the near future, when the FE codes have made some steps further and the checking codes like the Model Code 2010 and the Eurocode 2 are developed further in the same field.

The results of nonlinear analysis can contribute to an acceptable extra remaining capacity of existing concrete structures.

6 Acknowledgement

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7 References

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