Safety aspects during construction steps in the design of concrete structures

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Summary

The flexibility of a modern concrete structure design needs the use of different tools to guarantee safety. The safety must be guaranteed during lifetime and during the construction stage time. The flexibility needs an open mind in using new materials and new construction methods, which often conflicts with the safety aspects of the structure. Today the engineer has the availability of using tools, minimising conflicts between new and old materials or new alternative construction methods. It will be practical tools in the near future by merging these tools into the common engineering design tools like the finite element method.

Keywords: Design, FE-modelling, stage analysis, probabilistic analysis, post-tensioned prestressed reinforced concrete.

1. Introduction

The safety aspect of a structure is guaranteed in common engineering practise by following the different guidelines or code checking [1]. The safety level of the designed structure can be subdivided into 3 levels. These three levels will be explained into part 2.

Often only the structure at the finishing construction stage is calculated and checked to the available deformations and stresses. A phased analysis allows the design engineer to calculate the stresses and deformations at every construction stage. Phased analysis is mostly a designer tool in dedicated codes. Examples in this field are the dedicated program codes of the cantilever bridge design. These program codes can also be used into the cable stayed bridge design and the suspension bridge design. Basic finite element in these dedicated program codes is the beam 1D element. But there become also common FE program codes, which have phased options. This opens the use of other element types, like 2D and 3D elements, in the phased analysis. Together with the available wide range of material property options in these FE codes, the design engineer gets more possibilities. The design flexibility is as high as the FE code options are.

Adding a probabilistic tool to the calculation procedure will give the probability of failure of the uncompleted structure at every construction stage. Designing the structure with the finite element method gives the design engineer the opportunity to split up the structure into structure parts related to the construction stages. The subdivisions of these structure parts are the elements on which the finite element method is applied. The flexibility into new alternative construction methods of structures can be made by an alternative split-up of the structure. Structure parts related to the new developed belonging construction stages can be set-up.

New materials with its own uncertainties in material behaviour can also be covered by the use of the reliability index. At that moment the material parameters aren't deterministic but stochastic.

2. Safety aspects

Level I reliability methods compute only whether or not the reliability is sufficient instead of computing the real probability of failure. Combinations of variables are taken in such a way that the failure surface is likely to be outside the boundary defined by the reliability index. Therefore the use of partial safety factors is used. These partial safety factors are related to the load cases and to materials.

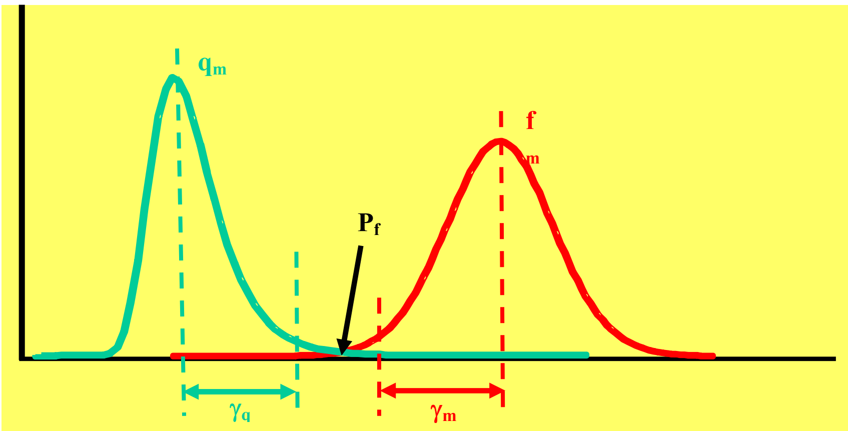

Fig. 1 Traditional design method level I including the partial safety factors

The present standard in level II methods is the First Order Reliability Method (FORM). An additional developed standard in level II methods is de Second Order Reliability Method (SORM). Both methods are unable to cope adequately with piecewise linear limit stat functions. A system analysis is required for these types of limit states. Other level II methods are the analytically or numerically computed gradient method and the non-gradient methods. Standard level III methods are the Monte Carlo method and the directional sampling method. These methods compute the probability of failure based on the exact probability density function and the exact limit state functions. Therefore they are considered being the most accurate. However these methods are very time consuming. The Directional Adaptive Response surface Sampling (DARS) method [2] is almost a level III method, which is not so time consuming. It allows the user (the design engineer) to switch to the Monte Carlo level III method, but the default switch restricts the user to a smaller amount of calculations with accurate results.

This means that the elapse time of getting the probability of failure is decreasing. Adding this tool to a common finite element code allows the design engineer to calculate the probability of failure of a structure (part) in every construction stage.

3. Development of the Directional Adaptive Response surface Sampling method

Structural codes require a certain level of structural reliability. The Dutch Building code, for example, demands a maximum probability of failure of 10-4 within a given reference period (lifetime of the structure). This probability of failure is ideally translated into partial safety factors by which variables like strength and load have to be divided or multiplied to find the so-called design values. These design values are to be used as input for a Finite Element Analysis. The outcome of the calculations is compared with the limit states (for example collapse or maximum deformation). The structure is supposed to have met the reliability requirements when the limit states are not exceeded.

Reality is different. First of all the method using partial safety factors makes it only plausible that the reliability requirements are met. There is, however, no certainty. A second aspect is that safety factors are often based on experience only. A link with the required reliability on a theoretical basis often does not exist. Third aspect is the system behaviour of structures. The safety factors are often derived for components of the structure for instance single sheet piles, anchors or single failure surfaces. A structure as a whole behaves like a system of these components. As a result, depending on the system under consideration, the structure can be more or less reliable than its components. Given these problems, it is useful to have a method to calculate an accurate (system) probability of failure of the total structure at once. Standard reliability methods compute the probability of failure given a limit state and stochastic parameters. Limit states might be for instance exceedance of yield stress in a structural member, exceedance of maximum deformation or global collapse. Well-known methods for computing the reliability are Monte Carlo simulation (MC) [3] and the First Order Reliability Method (FORM) [4]. In this paper an unusual method is applied: an adaptive method based on Directional Sampling (DS) [5]. For large and complex structures it is almost impossible to provide an explicit limit state function. Points of the limit state function can however be calculated using the Finite Element Analysis (FEA).

The problem arising is that the mentioned standard reliability methods are traditionally used for problems with only a few random variables using little time to evaluate the limit state function. In combination with FEA, the opposite occurs as there are many random variables and evaluating the limit state function takes much computational effort. The standard reliability methods in combination with FEA lead to a computational effort that is just too much. To speed up the computations, research at The Delft University of Technology has lead to the introduction of the so-called "Directional Adaptive Response surface Sampling" (DARS) [2]. In short the improvement to the standard directional sampling lies in the use of FE for the important directions and a response surface for less important directions. In practice this means that after the response surface is constructed, only a few FE computations have to be carried out.

In the DARS procedure, for the construction of the response surface all variables are varied individually and increased or decreased until failure. A FE model with n stochastic variables gives 2n (directional) samples in the principal directions. Consequently a quadratic response surface is fitted to these results. Following this starting procedure the random directional sampling takes place. The response surface is used in case of a large distance from the origin to the response surface. FE computations are used to calculate the real distance in case of a small distance from the origin to the response surface. In that case the response surface is updated (adapted).

Influence factors give insight on the importance of stochastic variables on the limit state. After finishing the directional sampling procedure, the influence factors □ are computed by means of a FORM analysis on the response surface.

Within the research project the probabilistic method is implemented in an existing FE code, namely DIANA [6].

4. Finite element method and phased analysis

Before a structure is finished, some construction stages should be considered. First casting a floor and after-wards casting an additional wall will give at least two stages. The addition of a phased analysis can help the design engineer to understand the effects of the typical construction method aspects at any construction time-step. Time dependent nonlinearities like shrinkage and creep depending of temperature can be taken into account in those phased analysis. On request also a temperature dependent nonlinearity can be added. The time steps related to the different construction stages define the time step a structure part is active or not. Meanwhile the material properties can change, creep and shrinkage can develop and loadings can be active or inactive. The stress results at the end of a construction stage are the initial stresses for the next construction stage. With this tool the complete lifetime of a structure can be simulated. Changing the structure by removing or adding a structure part is no longer a design problem on the FE method level. The biggest problem is the total elapse time of the full phased analyses. But when the design process needs it, inside the phased analyses it is easy to skip some nonlinearity temporarily by switching off nonlinear options. At that moment only the construction method is a research aspect and not the calculated values of the real stresses or deformations.

Hereby every construction stage of a structure can be analysed at every time step. During the construction period of the structure, a phased construction analysis can be running parallel on the design office to control the stresses and deformations on the site.

In this way the cantilever, cable stayed and suspension bridges with either its own construction stages can be simulated at every time step.

Fig. 2 Construction stage of a cable stayed bridge

5. New materials and new construction methods.

The use of new materials is strongly related to the development of the belonging guidelines. The acceptance of those guidelines will always be in discussion, but to minimise this discussion a design including a probabilistic analyses can be an alternative design method. By thinking into safety aspects of structures upon the usual results like stresses, strains and deformations, a new material can be accepted. An example in this field is strengthening of concrete structures by external carbon fibres. There are no standard checking codes in relation to concrete structures for the carbon fibres. Additional international guidelines like the FIB guideline and some national guidelines (UK and the Netherlands) are available for the design engineer. However, all the governmental authorities aren't convinced of the success of this new material in the civil engineering practise. Experimental test work can deliver material properties of new materials. These variation values lead to stochastic values. Each parameter gets its own mean value, standard deviation and distribution type.

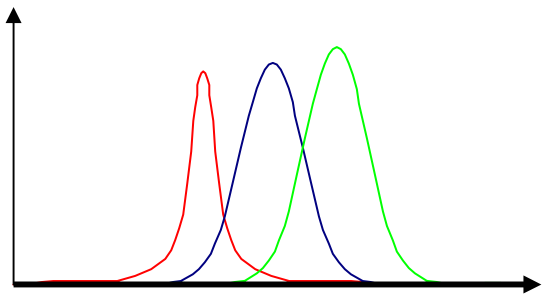

Fig. 3 Different distribution from lab tests

The distributions, which are at this moment allowable are Normal, Lognormal, Weibull, Exponential, Gumbel en Beta. Some distributions can be shifted or truncated.

When the FE code allows the designer to give the stress-strain relations as material property input for new materials, the designer is able to calculate the effects of these materials to the overall structure behaviour.

By using the FE method, studies can be set-up in this field to underpin these guidelines in a more elementary way. In the case of the already mentioned carbon fibres, the strength of the fibres and the epoxy between the fibres and the concrete structures can get a stochastic input into a FE model calculation. The tension and compression behaviour can be set-up like a uniaxial stress-strain relation. With this stress-strain input, the delamination of the fibres and concrete structure can be simulated in relation to the increase of a load to a simple girder structure.

The first shear crack in the girder is the base of delamination of the carbon fibres from the concrete girder. This is one of the mechanisms of failure by delamination in the guidelines.

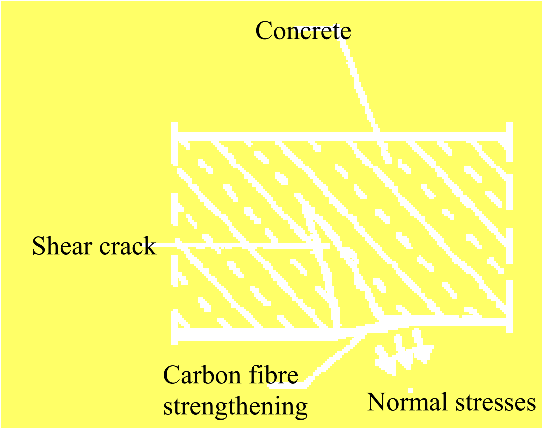

Fig. 4 Shear crack strengtening girder

So point of departure of this study was a cracked concrete girder, which will be loaded till failure. Laboratory experiments have shown a short load increment between the first and last step of delamination. The smeared crack approach delivers crack areas. Adding discrete shear cracks to the girderpositions allows the simulation of delamination. Refinement of the FE elements beside the shear crack and the mentioned stress-strain relation can simulate this type of failure.

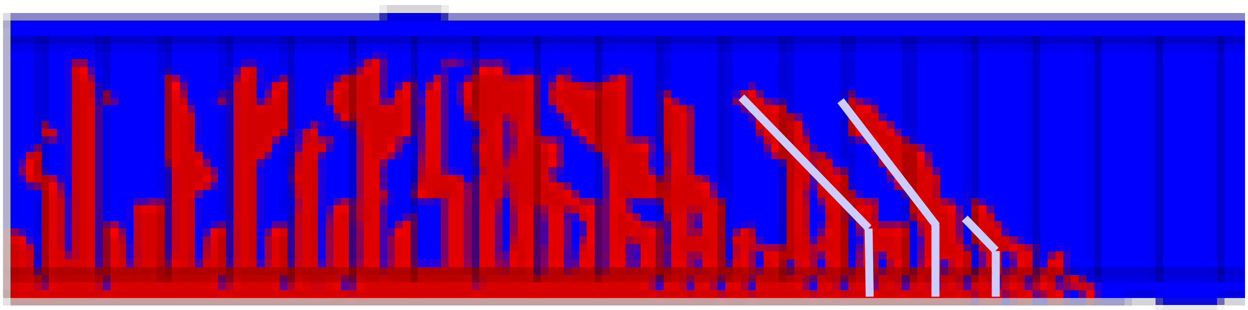

Fig. 5 Crack areas of the finite element model girder

Adding the probabilistic tool to this FE calculation gives the designer not only an idea of the behaviour, but also a reliability index of this girder structure. Beside this reliability index, the influence factors of the stochast parameters to this index can be calculated.

In relation to the flexibility of the chosen construction method, the FE method allows already designing alternatives. When the structure is already divided into several construction stage structure parts, a phased analysis approach needs no exceptional more time. The designer is free to choose how many FE elements are needed in a construction stage structure part. The design flexibility in looking to alternative construction methods by using the FE phase analyses method is very high.

6. Combination of probabilistic and phased analyses

The development of the probabilistic tool DARS, which is much faster then the original Monte Carlo method, gives the designer of structures the opportunity to add a probability of failure to the common results, like stresses and deformations. Adding this method to the usual FE method, including the phased analyses option, gives the designer a large flexibility in designing structures. This numerical probabilistic process converged like a common nonlinear numerical process. In a nonlinear numerical process the load deformation relation or stress strain relation is the leading part.

In a probabilistic analysis the variation of the reliability index against the number of samples or the reliability index itself against the number of samples is leading.

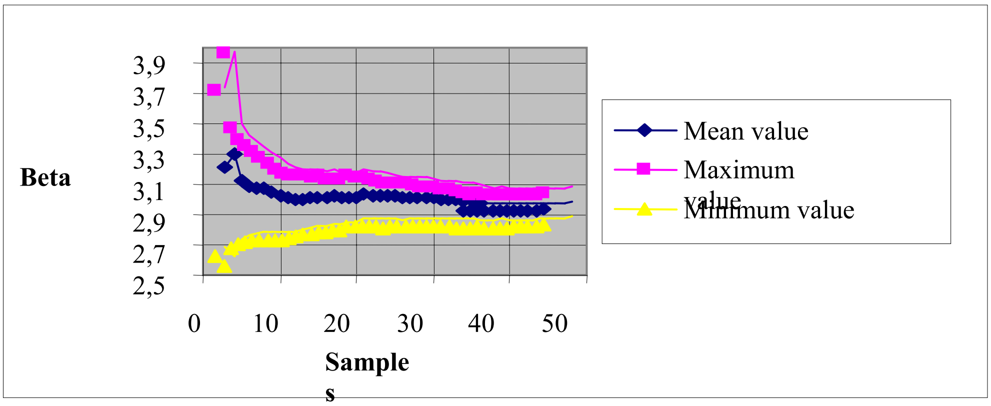

Fig. 6 Convergence process of a probabilistic analyses

The figure shows the example of the earlier mentioned strengthening of a concrete girder by carbon fibres. It shows a rather good convergence of the variation of the reliability index against the number of samples. The final reliability index β gets the value of 2.99 with a belonging variation of 0.10. At this stage it is a good result.

7. Conclusions

The combination of the above described safety aspects and the FE method will give the design engineer a new tool. Beside the control of the stresses and deformations at every time step, it is now allowable to control the probability of failure at each time step too. Changes in construction stages on the site can be simulated parallel at the design office including the result of a probability of failure at that particular time step. Also the effect to the next construction steps can be given in a range of probabilities of failure for each next construction step.

8. References

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