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Opportunities for Design of Structural Dimensions

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Introduction

It is regularly mentioned that most costs of a project are determined by decisions in the preliminary design phase. This is certainly true, however, also the subsequent phase, in which structural dimensions are determined and joints are detailed, has a substantial influence on the total structural costs. For example, a recent finite element analysis of the dome roof of a reinforced concrete LNG tank showed a safety factor of almost 5 for the dominant load combination [Nakano 1998]. There is clearly no need for such a high reliability and considerable economies would have been possible for this design.

To date, advanced analysis software can be used in the design process in addition to rules from codes of practice and engineering judgement. This opens the way to improve the quality of structural designs. In Civil Engineering, a design process that includes realistic simulation software is often referred to as *performance-based design*. Examples are the earthquake response of a reinforced concrete shear wall in a high-rise building, the durability of concrete in a marine environment and the spread of fire in a building. In Mechanical or Aircraft Engineering, such a process is often referred to as simulation-based design or virtual prototyping.

The designer should be in charge

In our efforts to advance structural design, many researchers concentrate on computational optimisation of the total structure. This is done rather rigorously in that the proposed dimensioning process is completely automatic without any human intervention. Important progress has been made in this field but practical applications are still rare. Other researchers focus on expert systems, which also have the potential of doing the work of an experienced specialist. Though both developments can become very valuable, the author feels that we should find ways to integrate them with the flexibility and creativity of a human designer.

However much automation might be possible in the future, structural design will not likely become a press-button action. For example, only a human designer can come up with the hazards and loads that a structure will possibly face during its live. Of course, the software could request loading and other data from an engineer, however, this actually makes the engineer an assistant of the software. Clearly, this kind of work is not what people prefer and is a situation in which they are prone to make mistakes. So, not the software but a designer should be in control. He or she should make the design, communicate with other members of the building team, check the design and take responsibility for it.

Perhaps the finite element program of the future will allow a structural designer to see the behaviour of his design with almost no delay. Voice commands might be: Show which limit states are entered where in the structure. Show the detailed behaviour of a specific part of the model entering a specific limit state. Show the redistribution of forces when a specific load combination is put at the structure. If asked for, the future software might assist a designer with an expert opinion, it might warn for possible mistakes or it might propose optimised dimensions.

Levels of detail in the design process

Simulation software is available on three levels of detail. Designers are already used to software on the *global structural level*, which are basically the linear-elastic structural analysis and linear-elastic finite element programs. Clearly, these are mostly used to estimate deformations and the flow of forces trough the structure.

One level of detail deeper is the *members-and-joints level*. On this level codes of practice are most valuable and many deemed-to-satisfy rules have been implemented in software. However, ever more programs become available to simulate the local structural behaviour. For example, the strength of a section of a reinforced concrete beam and the behaviour of a steel plate joint. In time, they will definitely replace the rules of codes, giving more accuracy and wider applicability.

The third level of detail is that of *material and interactions between materials*, for example the formation of cracks in concrete and their interaction with a reinforcing bar. On this level, software can be expected too, for example to simulate the durability of the local material.

Structural design often proceeds top-down. It typically starts at the global level, continues with the members-and-joints and ends with the materials. However, going up a level in a new design cycle is not uncommon and should definitely be possible in any future software that supports the whole structural design process.

Evolution of structural design

To date, performance-based design becomes feasible mainly because computers have become sufficiently fast. Ideally, processing all jobs[1] in a design cycle should be done in less than a few minutes on a normal personal computer. Some engineers believe that a processing time of 30 minutes still can be acceptable if the computation takes place in the background so that the computer is available for other tasks. Clearly, a subsequent design cycle should be started only if the expected economies are worth more than the time spent by the designer. In addition, a long computation time can be annoying because the designer might have forgotten what he or she was doing when a computation is finally done.

Geometrical nonlinear behaviour of frame models (p-Δ effect) is already included in many commercial structural analysis programs. For example, in Germany these analyses are common practice and supported by the German code (DIN). Recently, also geometrical nonlinear plate elements have been introduced [ESA-Prima Win]. Physical nonlinear behaviour is available for reinforced concrete structures on the members-and-joints level [WCOMD] [SBETA]. Software for the global nonlinear dynamic behaviour of reinforced concrete frames has been available and used already since 1972 [Kanaan 1973]. However, to the best of the author's knowledge, this program has not been implemented in a commercially available graphical user-interface as yet. Clearly, advanced analysis software increasingly will find its way to engineering practice and the development of performance-based design will continue.

When computers have become even faster, two developments will be possible: design optimisation and reliability-based design. Optimisation of linear models is already available in the finite element package MARC [MARC]. However, this software is for exceptional projects only because it runs on a UNIX workstation and requires a trained specialist. Realistic nonlinear optimisation of for example 5 design variables in 10 iterations will require 50 repetitions of every job. If we assume that computers continue to become twice as fast in every 18 months, it will take approximately 8 years before computers are 50 times as fast as today. So, in 8 years, optimisation could be integrated in performance-based design. For example, in the final design cycle we could use it to economise an extra percent. Perhaps it even might be used in an earlier cycle if we can find a way to easily formulate the many boundary conditions that any practical design has.

As stated above, the other promising development is reliability-based design. Today's personal computers are already fast enough to support reliability-based design on the level of members-and-joints. However, really designer-friendly software has not surfaced as yet. The software that is commercially available needs an expert user to derive limit state functions and to find probabilistic load data [VAP] [COMREL]. Perhaps the largest obstacle for reliability-based design is that it is often unclear how the reliability of a single component contributes to the total reliability of a structural system. Therefore, we might need to wait a few years until computers will be able to compute the reliability of complete structural systems in a few minutes. For a normal reliability computation (first order second moment approximation) a job needs to be processed roughly 20 times. On the other hand, some of the conventional jobs related to load combinations become redundant[2]. Perhaps already in 6 years, reliability-based design will be successfully introduced in the design process[3].

Reliability-based optimisation seems to be the subsequent natural step in the development of structural dimensioning. To plan further than that seems to be rather speculative. The author feels that no person has the power to really change the development. We merely have the choice to contribute to it or not.

From theory to practice

Though, performance-based design is quite different from conventional design, it can be expected that it will be easily adopted. Clearly, engineers are comfortable with the concept that structures need to perform as specified. Advanced nonlinear models will just reduce the number of deemed-to-satisfy rules that are being used nowadays. It will shift our sense from "being confident it will work well" to "knowing it will work well".

Some engineers in seismic design already have started to use performance-based concepts and included it in codes of practice. Nevertheless, it is difficult for design engineers to take initiative because performance-based design without software that supports all steps in the process will take more time than a conventional design process. So, software engineers are most important in the development. Fortunately, there is considerable competition in the market of structural design software and, as written above, already the first nonlinear models have been implemented.

Structural designers together with academic researchers should apply the advanced - but often user-unfriendly - software models in well documented pilot designs of realistic structures. These projects will show software engineers the way for building the structural design software of the future.

Safety factors (load and resistance factors) should be diversified to take into account the accuracy of the structural model and load models applied. Clearly, the more accurate the models, the smaller the safety factors can be. For example, the Japanese code for structural concrete LNG tanks distinguishes three design models with different complexity, accuracy and different load factors [LNG tank code 1999].

In addition, design procedures for specific structures and structural parts need to be developed because it is often not obvious how to obtain a sufficiently optimised design in an acceptable number of design cycles.

Summary

Performance-based design has the potential of creating high quality structures for reduced costs compared to traditional deemed-to-satisfy design. In addition, it can offer the flexibility to create even more challenging structures of exceptional shapes and dimensions.

Developments in design of structural dimensions are driven by the increasing computational speed of modern personal computers. To date, performance-based design starts to supplement and replace deemed-to-satisfy design of Civil Engineering structures. In 6 to 8 years, reliability analyses or optimisation can be introduced in design processes.

Footnotes

1. In this paper the word *job* is used for a structural model including a load combination. The structural model represents a construction stage, a design alternative, design improvements or missing elements. As usual, a load combination is a series of load cases in a specified order, which can include supports, applied tractions, applied displacements, temperature changes, pre-stress and material shrinkage. In each design cycle, often a substantial number of jobs need to be processed.

2. Load cases can stay constant in time (e.g. dead load) or can change in time (e.g. wind

load). Load combinations due to uncertainty in constant load cases are replaced by a reliability analysis, while load combinations due to uncertainty in time still need to be processed.

3. Often, reliability analyses are not useful in first cycles of the design process because we need load combinations to compute the force flow and subsequently section forces to select dimensions. Otherwise, designing could become a trial-and-error process with a very large number of cycles.

Literature

1. Nakano M, Kawamura Y, Kuroda M, Niimi K, "Design of R.C. Domed Roof of the World's First LNG Underground Tank", *Proceedings of the 8th Conference of the Japan Society of Mechanics*, Design Engineering and Systems, Nov., 1998. (in Japanese)

2. Japanese Design Code on Underground Reinforced Concrete LNG Tanks, Draft June 1999, *Japan Society of Civil Engineers*. (in Japanese)

3. Kanaan AE, Powell GH, "A General Purpose Computer Program for Inelastic Dynamic Response of Plane Structures (Drain-2D), with User's Guide and Supplement", *EERC* Reports No. 73-6 and 73-22, University of California, Berkeley, April 1973 and August 1975.

About the author

Pierre Hoogenboom is born in 1965 in the Netherlands (Europe). He attended technical schools on carpentry, building site management, and structural design. After working a few years in both construction and design companies he started to study Civil Engineering in Delft University of Technology. He got a Ph.D. degree in 1998 for developing a nonlinear model and software for design of structural concrete walls. Currently, he is lecturer in the University of Tokyo where he implements performance-based design.