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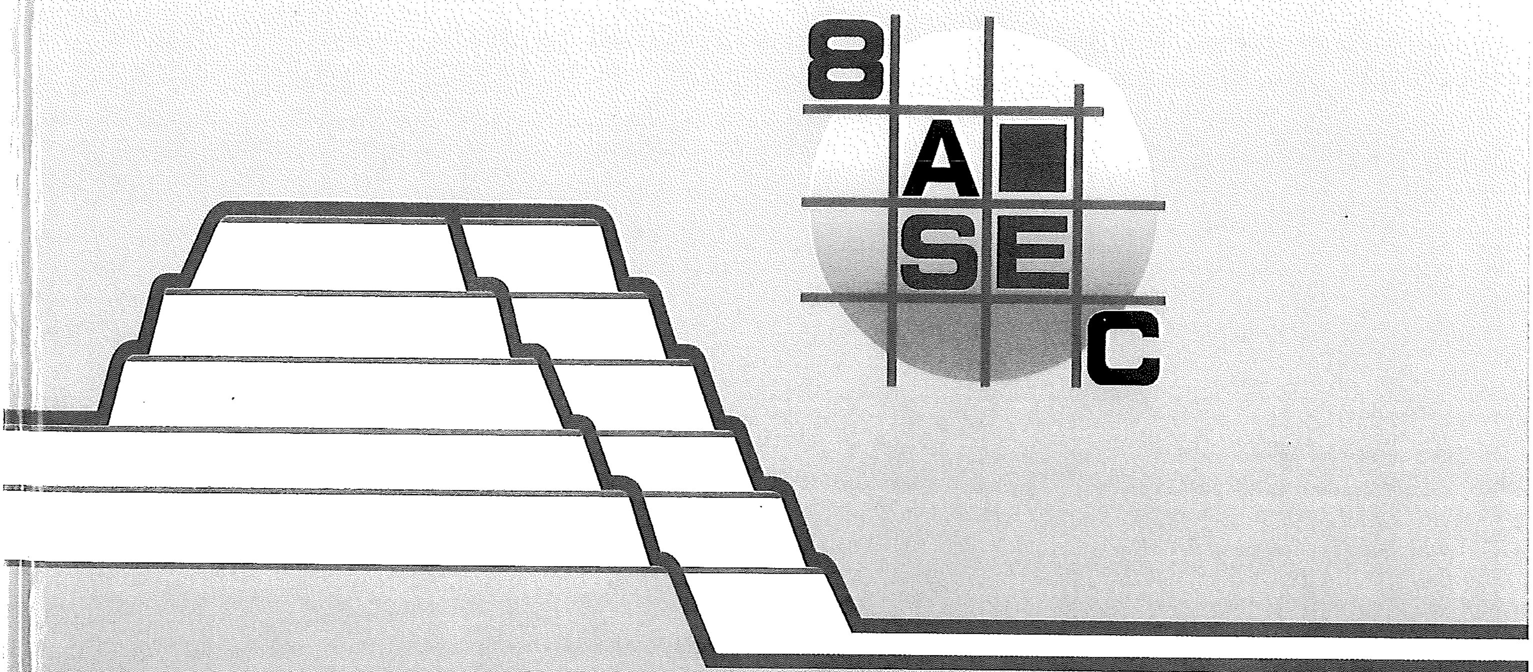

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تطبيق النماذج المتطورة فى التصميم الإنشائى

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١باحث بجامعة ديلفت للتكنولوجيا ، هولندا
٢مدرس بقسم الهندسة الإنشائية ، جامعة القاهرة
٣رئيس قسم الهندسة المدنية ، جامعة طوكيو باليابان

ملخص: يناقش هذا البحث تطبيق البرامج المتطورة فى التصميم الإنشائى ، ويعتد هذا البحث بنماذج المـــواد ونمـــاذج المنشآت كروابط بين المستويات المختلفة فى عملية التصميم الإنشائى . ويوضح البحث مزايا التصميم بطريقة سـلوك المنشأ والإمكانات المستقبلية لها ، كما يبين أن النماذج ذات التفاصيل الدقيقة قد تكون غير مرغوبة من وجهـــة نظـــر المهندس المصمم .

الكلمات الدالة: التصميم بطريقة سلوك المنشأ ، النماذج الإنشائية ، عملية التصميم ، مستويات الملاحظة .

APPLICATION OF ADVANCED MODELS IN STRUCTURAL DESIGN

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Abstract: This paper discusses application of advanced software models in design of structural dimensions. It considers material and structural modelling as connections between levels of observation in a design process. Advantages of performance-based design and future opportunities are addressed and it is demonstrated that much detail in a model can be undesirable from a designer's point of view.

Keywords: Performance-based Design, Structural Modelling, Design Process, Levels of Observation.

INTRODUCTION

Due to the ever-growing computer capacity, it becomes possible to include more detail in structural models. For example, to date, programs are commercially available to accurately simulate the complicated response of reinforced concrete [1,2]. The under-laying material models can include crushing of concrete, hysteretic behaviour of concrete and steel, stress transfer in cracks and debonding of reinforcing bars. These programs are developed as user-friendly Windows applications for personal computers. So, with some practise, we can handle them conveniently.

Advanced software models are used for many objectives. Some are applied to gain deeper understanding of material and structural performance. Many models are used to validate and extrapolate design rules in codes of practice. Also, software models are applied to check the completed design of complicated structures. However, increasingly the advanced models are directly applied to design structural geometry and dimensions. This paper will focus on the latter development. In mechanical and aircraft engineering it is often called *simulation-based design* or *virtual prototyping*. In civil engineering it is called *performance-based design.*

MODELLING STRUCTURAL BEHAVIOUR

The academic community produces engineering models of many types and complexities. In this paper we organise the models in three groups, which link four hierarchical levels of observation that are common and convenient in both engineering science and practical design. This section provides a framework for the subsequent sections of the paper.

The following levels of observation are distinguished.
1) Structure
2) Members, joints or parts
3) Constitutive continuum
4) Material constituents

Structural Models: The link between level 1 and level 2
Many structures can be subdivided into structural members – like beams and columns – and their joints. When members cannot be distinguished the structure can be divided into convenient parts. Simple macro elements are available for the behaviour of these components. As an example, Fig. (1) shows the cyclic moment-curvature relation for sections of members implemented in software IDARC [3]. Software can compute the interaction of the components under several load combinations. The structural models can be three-dimensional, geometrically nonlinear and physically nonlinear. To date, large models with dynamic loading still take a night to be processed, but with some planning of the design process this is not a serious problem.

Component Models: The link between level 2 and level 3
As an example, Fig. (2) shows a finite element model of a joint of a steel I-beam and a reinforced concrete column [4]. Nonlinear finite element models typically apply averaged or smeared field quantities (level 3) for the response of materials. Sometimes, standard material models of computational mechanics are selected. For example, a Mohr-Coulomb material for soil or a Drucker-Prager material for concrete. Often, special phenomenological material models need to be used, for example, to describe cyclicly loaded reinforced concrete [5].

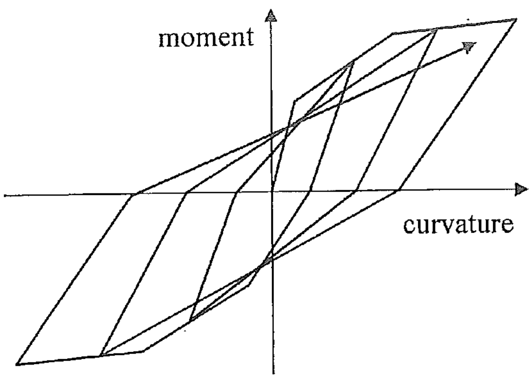

Fig. (1): Hysteretic model for moment-curvature behaviour of beam sections

Material and Connection Models: The link between level 3 and level 4
Many detailed models have been proposed to describe structural materials including their constituents. For example, models that take into account individual cracks in concrete and debonding and local yielding of a reinforcing bar [5,6] (See Fig. (3)). Other models describe shear banding and necking in metals or shear planes in soils. These models are used to derive and calibrate phenomenological material models of a continuum (level 3).

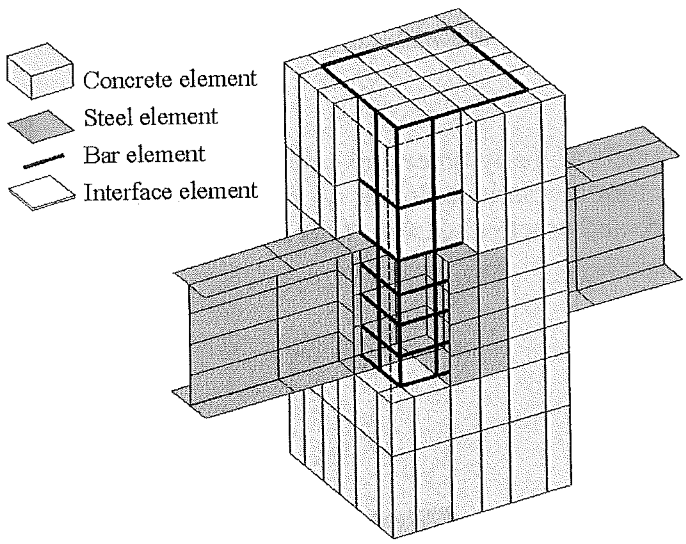

Fig. (2): Model of the joint of a steel beam and a reinforced concrete column. Some of the concrete elements are removed to show the reinforcement arrangement.

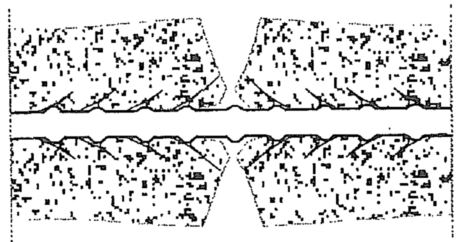

Fig. (3): Micro cracks in concrete around a tensioned reinforcing bar [6]

PERFORMANCE-BASED DESIGN

In traditional design procedures we use rules from codes of practice to determine structural dimensions. In decades of application the rules have evolved and are now deemed to give safe results. Occasionally, there is sufficient support to improve them, for example, after a disaster like an earthquake or a tornado. In addition, new rules are introduced when new structures, new materials or new theories have been developed.

Of course, these rules have also been implemented in software for structural design. However, many agree that we can do far more with computers than only automating cookbook rules from the slide rule era. Instead, we can use realistic computational models that have been developed in research institutes. This is usually referred to as performance-based design. In performance-based design the actual way in which the design is obtained is immaterial, as long as can be shown that the final result does not fail. In the design process the structural response is simulated for each load combination in order to evaluate if a limit state occurs. If the performance is not sufficient, the design needs to be improved in a subsequent design cycle.

As an example, Table (1) shows proposed earthquake performance requirements for buildings in California, USA. In this table, reliability is defined as the probability of not being exceeded during a 50-year period. The right-hand two columns of the table are interesting for the building owner because it can be used to balance risks in financial decisions. A responsible owner will insure the property or create funds for possible future repairs. Alternatively, he or she can decide to invest in extra strength and provide additional or deviating performance requirements to limit possible future damage.

The designer has to translate the reliabilities into design loads and safety factors (left-hand column). This is not an easy task. For example for earthquakes we need to look at nearby active vaults, the distances of the vaults to the site and the soil at the site. Fortunately, commercial software [7] is available to assist the designer and for many regions in the world, geologists have made maps of the local seismic hazard.

Table (1): Performance requirements for ordinary buildings according to Vision 2000 [8]

Load	Reliability	Limit State
Small earthquake	0.50	No significant damage to the structure. It retains nearly al its strength and stiffness. Most non-structural components function. Building use impaired.
Medium earthquake	0.90	Significant damage to structural elements, with substantial reduction in stiffness. Non-structural elements may not function. Use prevented until repair.
Maximum credible earthquake	0.98	Near collapse. Substantial structural and non-structural damage. Some falling debris.

There are three potential advantages of performance-based design
1) Economies in materials and labour
2) More reliable structures
3) Streamlined design process

The first advantage relates to the average of the error that we make with a model. It seems that this average for advanced models is only smaller for some structural elements. For example code rules ignore membrane forces in structural concrete floors that are supported at all edges. Software models can capitalise on this hidden strength. However, in many structures and structural elements, designing with a nonlinear model may give a different distribution of material but the total quantity is not much less.

The second advantage relates to the standard deviation of the error that we make with a model. This standard deviation is usually smaller for advanced models because they are obviously more accurate than code rules. So, in time, safety factors in codes of practice could be reduced. Alternatively, next to the normal safety factors, reduced safety factors could be included for design with advanced models. This long-term advantage gives little impetus to the introduction of nonlinear models in design. However, when current design clearly shows to be insufficient, performance-based design can be a solution. For example, shear failure of reinforced concrete columns, as shown by the earthquake in Kobe in January 1995 [9].

The third advantage is not easily recognised because a nonlinear model often requires more design cycles than a linear model. The advantage is that at one level of detail just one model can be used for all load combinations, all construction stages, design alternatives, for both ultimate and service limit states and for any kind of structural response. The software can check the performance with just a press of a button. This makes the design process more transparent than current practice, where numerous models and rules are being used next to each other. Obviously, much – if not all – depends on the user-friendly software that implements performance-based design.

DESIGN PROCESS

Structural design typically proceeds top-down along the levels of observation of Section 2. Performance-based design can be applied between each level of observation. We generally start with the whole structure and determine sufficient performance of the members and joints. This usually involves a few design cycles. Subsequently, the members, joints and other components are designed, which includes selecting dimensions and requirements of materials. Clearly, this also involves some design cycles for each different component. Finally, composite materials and details are designed considering strength and durability requirements. For example, concrete mix proportions, reinforcing details or aluminium laminates.

Despite the essentially top-down process, it is not unusual to go up a level because initial assumptions might be difficult to fulfil later in the process. For example, initially we might assume that a floor thickness of 250 mm will be sufficient, to find out later that it needs to be at least 270 mm thick. Probably, in that situation, we need to go back and make changes like adjusting the story height.

Performance-based design can be time consuming because it is not always obvious how to improve a failing design. For example the software can show that a simple deep beam design cracks heavily and fails prematurely but it is not clear if the vertical shear reinforcement, the distributed horizontal reinforcement or the horizontal bottom reinforcement should be strengthened. Even if we can identify a cause of failure, it is not clear how much extra reinforcement is needed to prevent failure. As a consequence the number of successive improvements can become large.

It was found that the design time reduces considerably, when a simple *linear-elastic* model is used to obtain a first estimate of the force flow. The initial dimensions can be based on this force flow, as is common in traditional design. Also in the subsequent design cycle it can be convenient to leave some materials or some components of the model linear. These are typically the elements that have not yet been fixed or can be changed easily. The other elements can behave nonlinear and the software can do *nonlinear analysis* to show the redistributed force flow. Subsequently, structural dimensions can be improved. As a final check, the performance of the design can be *simulated* for all load combinations with accurate nonlinear behaviour of the components. This three-step design procedure – 1) linear, 2) partially nonlinear, 3) completely nonlinear – has been applied in design of reinforced concrete walls [10].

FUTURE IMPROVEMENTS

The increase of computation power of personal computers is expected to continue for many more years. Therefore, in the near future we could replace the third step in the design procedure by discrete *material optimisation.* In this concept, the designer can select several options for dimensions of a structural component. For example, next to 4Ø16 = 804 mm^2 reinforcement we could additionally pick 7Ø12 = 792 mm^2 and 2Ø20+Ø16 = 829 mm^2. Subsequently, the software can perform simulations for all selections and present the dimensions that both fulfil the performance requirements and need the least material.

Instead of optimising over selected alternatives we could also optimise over a large standard database. However, this might be less successful because usually there are many database solutions that are not suitable for a particular situation. For example Ø32 = 804 mm^2 reinforcement may be too heavy to carry by workers. Perhaps an expert system could filter out most of the impractical solutions but it is doubted if this can replace the knowledge of a human designer on the particularities of a construction project.

We should not expect large savings by applying optimisation. Most designs are already quite good after the first two steps of the design procedure. Perhaps a few percent can be economised of the structural costs by capitalising on redistributions at the maximum load. Nevertheless, this can be worth much more than the small extra design effort.

The subsequent upgrade of future software seems obvious: Instead of checking if no limit state occurs, the software could also check whether the *reliabilities* of the limit states are sufficient. This will be less conservative than using traditional safety factors and load combinations. However, the method can only be applied in the last design cycle because it does not give information to quantify design improvements. So, it is rather a computational upgrade than that it affects the design process.

Finally we could improve the software by *economical optimisation* of the project cost plus expected failure costs. This can replace both the optimisation of material quantities and computation of reliabilities of limit states. It can be useful because the economical optimal reliability can be larger than the minimum reliability needed to protect live and society. However, it will take at least ten years of computer hardware development before we can consider introducing this in engineering practice.

DETAIL IN STRUCTURAL MODELS

The current development in engineering science is towards more detailed models. However, do we really need all this detail in design models? *From a design point of view, a model does not need to describe the detailed response of a bad structure. Instead it needs to show how we can make improvements to obtain a good structure.*

Example 1
Structural models are available for the nonlinear behaviour of reinforced concrete frame buildings. These models can accurately describe failure of beams, columns and joints [11]. So, they can be used to simulate the response of existing high-rise buildings under earthquake loads. From an academic point of view this is very interesting and considerable effort has been invested in the development of software.

However, the retrofit recommendations derived from such advanced simulations are usually very simply: strengthen the columns and joints that failed. The beams are allowed to yield because that provides a safe mechanism to absorb energy from an earthquake. For this simple recommendation we do not need to build a detailed model. Instead, we can make a far simpler model that only includes bending failures of the beams. The failing members do not need to break but can just yield indefinitely. Processing this model will show where forces and moments become too large or where beam ductility is insufficient. Clearly, the insufficient members and joints should be retrofitted.

With the simple model we arrive at the same design result as the detailed academic model. The advantages are that it requires less effort to provide the model data and – more importantly – with the simple model we need far less design cycles because the results not only show what should be improved but also how much it should be improved.

Example 2
Nonlinear finite element models have been developed for reinforced concrete deep beams. From an academic point of view it is definitely very interesting to accurately include debonding of reinforcing bars in these models [12]. Debonding of the reinforcement can strongly affect the ultimate performance. It can show how failure develops and what ductility is available. However, generally, a designer does not want debonding bars. He or she wants forces to develop in the bars because that is their purpose in the first place. So, from a design point of view, debonding behaviour does not need to be modelled. The software only needs to show the shear stress at the interface of bars and concrete. If the shear stress becomes too large, debonding needs to be prevented by anchorages like hooks, bends, development length or heads.

The advantage of the simplified model is that we can do the analyses for all load combinations and provide anchorages in one sweep. With the detailed model we would have to interrupt an analysis every time debonding occurs somewhere and provide an anchorage before starting the computation all over again. Clearly, the simplified model speeds up the design process considerably.

Example 3
Several reinforced concrete underground waterpower plants are under construction in Japan. Typical for these structures are a large temperature difference between the warm generator and the cold turbine (See Fig. (4)). In addition, substantial hydration heat develops during curing of the concrete in these monolith structures. It is tempting to perform realistic nonlinear finite element simulations of their performance, which would include dispersion of heat, expansion of the material, cracking of the concrete and yielding of the reinforcing steel. However, when concrete cracks its stiffness is strongly reduced and the temperature related stresses almost disappear. Consequently, redistributions of the force flow due to temperature load appear to be small and for design of reinforcement we can safely ignore these loads.

The advantage is that the computation time is strongly reduced. It would take weeks to process nonlinear simulations of the structural performance for all load combinations because of the large number of elements in such a tree-dimensional structural model. Moreover, for many structures, it might be sufficient to process a linear model as long as load combinations including temperature are ignored.

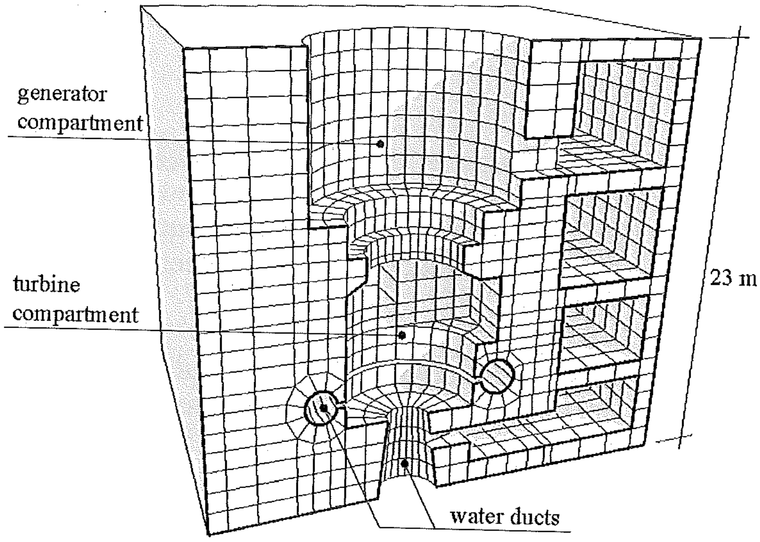

Fig. (4): Cross section of the monolith reinforced concrete structure of a hydropower plant

Example 4
In design of reinforced concrete walls with openings we need to consider redistribution of the force flow due to cracking of the concrete [13]. Clearly, for checking structural performance, safe values for the strengths of the materials need to be used (appropriate resistance factors). However, low strength concrete has a low stiffness, which influences the force flow. This is not realistic because if the structure fails it is most likely that only in some critical location the concrete would be of poor quality (design point concept). In most of the wall the material would have an average quality. Therefore, the material model for simulating performance must be a compromise with average stiffness and safe strength.

In this context, the simple bi-linear model for concrete in compression is better for design of walls than a detailed polynomial model (See Fig. (5)). Of course, this problem would not exist if the reliability of the structure would be evaluated with the stochastic finite element method. However, this method is not yet sufficiently developed for practical application.

Despite these four examples, there are many situations where the structural model should include the complete and detailed failure behaviour. For example, when we opt for a maintenance and repair strategy, or when we want to optimise a design in the ultimate limit state.

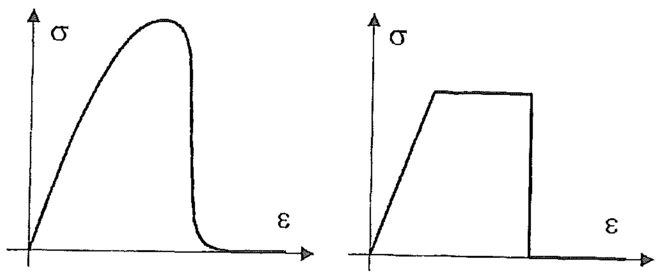

Fig. (5): Response of compressed concrete. Left is shown a detailed polynomial derived from test cylinders. At the right-hand side is shown a compromise for design with average stiffness and safe strength.

CONCLUSIONS

Advanced software models can be applied effectively in design of structural dimensions. For this it is essential to recognise that structural design takes place at different levels of observation. The models are used to link data of these different levels. Design procedures are being developed that give a good result in an acceptable number of design cycles. Typical of these procedures is that the models sometimes ignore some features of the real properties, real load or real behaviour in order to obtain a quick convergence of the design process. Examples discuss the design advantage of 1) models that show needed strength or ductility, 2) analyses that are not interrupted by local failures, 3) ignoring load cases that hardly contribute to the response, 4) reducing material strength independently of its stiffness.

Performance-based design needs software that supports all steps in the process. Without this, it takes more time than a conventional design process due to laborious keying of input data and interpreting output data. So, software engineers are most important in the development. They need to build the environment in which the models can be used. Fortunately, there is considerable competition in the market of structural design software and advanced nonlinear models are increasingly implemented in commercial design programs.

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