A REVIEW OF FEA TECHNOLOGY ISSUES CONFRONTING THE CIVIL ENGINEERING INDUSTRY

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SUMMARY

Finite Element Analysis technology issues are addressed for applications of the deep underground, soil mechanics, transport infrastructure and buildings. These application areas originate from both the civil construction and the petroleum engineering sectors. The main business drivers in these sectors are identified and explained and the purpose of Finite Element Analysis is brought in relation to the business drivers. The state of practice of Finite Element Analysis in each of the 4 areas is described extensively and illuminated with examples. Finally the general technology needs and topic for research are discussed.

1: INTRODUCTION AND DEFINITION

The civil engineering industry sector is wide and very fragmented. It was assumed that this sector is not restricted to buildings and transport infra-structure but also includes soil mechanics and the deep underground. For these four areas the following characteristics apply:

- engineering practice is strongly affected by national legislation;
- projects are typical one of a kind;
- in Europe usually the responsibility of the design-phase, the construction-phase and the maintenance-phase of a structure are allocated to different parties. Recently there has been a move by contractors to take over responsibility of the design phase too. Accordingly, consulting companies are hired by contractors in these cases.

Although Finite Element Analysis is not a necessity for building new structures, and only a few design codes recognize the design by analysis approach until now, it has found a respectable position in the design of innovative structures and new concepts. Finite Element experts often feel that the design codes represent a barrier to more intelligent use of Finite Element Analysis in design of structures. In general the design models are large, the analyses are most of the times only linear elastic and strongly schematized, whereas typical construction materials such as reinforced concrete, masonry and soil behave essentially non-linear and are inhomogeneous in nature. Therefore the interpretation of results is handled in general conservatively.

In Europe, the money spent annually on maintenance, repair and renewal is approximately equal to the money spent on new construction. Hence there is a growing need for reliable tools for assessment of the performance and safety of existing structures. The widespread deterioration of reinforced concrete infrastructure represents a particular challenge. Also there are new aspects of interest arising such as damage to existing structures as a result of excavations and underground construction in populated areas and fire-resistance of buildings and tunnels, with a high impact on public interest. There still is relatively little experience with these aspects and design codes first start to address these items. Finite Element Analysis is proving to be a useful tool for getting a better understanding of these phenomena and for quantifying failure of structures as result of these factors. Advanced Finite Element analyses, which address these phenomena, deal with highly non-linear material models, different interacting physical effects and detailed models. Towards the civil construction industry the challenge for the finite element world in the coming years is to make these advanced finite element techniques more efficient and easier to use for application engineers.

In the following an overview of typical Finite Element Analyses applications in each of the 4 areas identified in the civil engineering industry sector is given.

Deep Underground

Deep underground construction is defined as more than 100 metres below surface. Typical applications are mining, tunnelling through mountains, straight crossings in the form of tunnels under deep fjords and gas/oil production from reservoirs. The material is usually rock and the effective stresses and pore-pressures are extremely high. Rock may show creep and failure as a result of pore-collapse. The model has typically the dimension of kilometres and is fully 3-dimensional. It should identify the different formation layers which might have arbitrary shapes. These formation layers are usually imported from geo-modelling software programs that interpret seismic logs into geometry data, which is used for the finite element meshing. The models may include slipping faults. The analysis results are surface subsidence, stress-changes, compaction strains, etc. The mayor challenges are the meshing of the irregular formations and mapping of properties and loadings to the element-grid, the material-behaviour and slipping faults. Figure 1 shows the subsidence due to pore-pressure reduction in a gas-reservoir at the top of a selected rock formation and at ground surface.

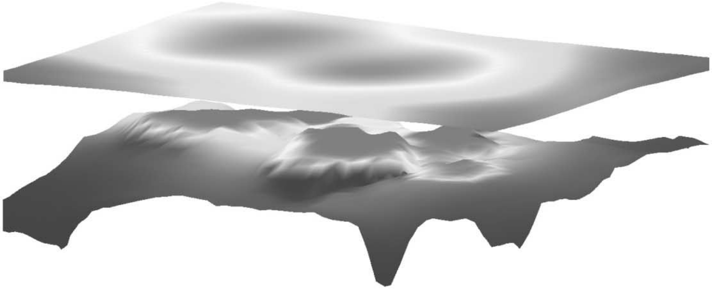

Figure 1: GEOMEC model with subsidence in oil-reservoir due to depletion.

Soil Mechanics

At less than 100 metres depth the underground usually consists of sand and clay layers. Because of lack of space in urban areas, the building of constructions in the underground gained in popularity in the last years. Soil is a highly porous material with pores filled with water. Loads on soil are carried by the matrix of grains and the water in the pores. Soil behaviour is essential non-linear and depends strongly on deformation history. Therefore, in geotechnical analysis the construction history should always be taken into account carefully by considering the different building phases. Typical applications for Finite Element Analysis are excavations in urban areas, tunnel construction, building foundations and natural dams/dikes which are saturated with water. Also extensive Finite Element Analyses were carried out for concrete gravity platforms in the North Sea. The most interesting analysis results are surface subsidence, soil forces on structures, soil compaction, shear-capacity of the soil and water-level development. Also groundwater flow and transport of environmental pollutants are applications of Finite Element analysis although there are not yet many examples of such analyses available. The major challenges are material modelling, especially for cyclic loading, assessment of material parameters and the interaction between soil and construction. In Figure 2 a 2-dimensional Finite Element model of an excavation with anchored (block) pile-sheet wall (green) is shown. The different stages of excavation are coloured blue and pink. First the ground-water flow is calculated and the pore-pressures are input for a following non-linear elasto-plastic stress-analysis. Frictional sliding applies to the interface of wall and soil.

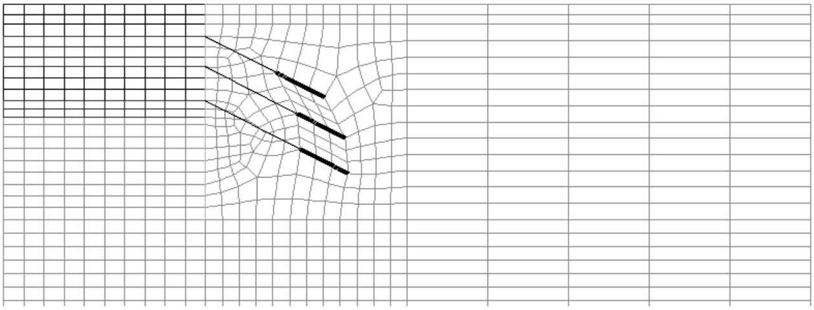

Figure 2: 2-dimensional excavation model with anchored pile-sheet wall

Transport Infrastructure

Structures for transport infrastructures are mainly bridges and tunnels. Bridges are composed of steel, masonry, concrete or composites. Analysis of existing masonry arch bridges is challenging. In the U.K. there are many such railway bridges now in need for repair or upgrading. Masonry structures behave anisotropic and the mechanical characteristics are highly nonlinear. Tunnel structures are mainly concrete and sometimes steel. Because of its limited capabilities of carrying tensile stresses, in most constructive applications concrete is reinforced by steel bars and grids in areas where tensile stresses are expected. Also tension cables may be applied to create a pre-stress loading in the concrete construction such that under operational conditions tensile stresses do not occur. Taking all these effects into account in a 3-dimensional Finite Element model is laborious because of the combination of different materials which each have their own failure characteristics. New applications of composite materials (GFRP, CFRP, AFRP) in bridge engineering will require improved modelling of failure of fibre reinforced materials. Also the loadings can be various: Dead weight for bridges, wind loads for bridges, traffic loads for bridges, ground structure interaction for tunnel-linings, fire loads for bridges, earthquake loadings for bridges, impact loads for tunnels and bridges, temperature loads. Finite Element models for transport infrastructures are usually built from scratch in the Finite Element environment. Only recently geometries are defined in CAD programs and imported into the Finite Element environment. The purpose of Finite Element Analysis of transport infrastructures can be many: calculation of the amount of required steel reinforcements in concrete structures; the calculation of extreme tensile and compressive stresses in the construction; deflections; cross-section forces and bending moments; ultimate failure load; stability etc. The major challenges are the modelling of the embedded reinforcement for reinforced concrete constructions and the concrete failure. In order to describe concrete failure correctly the different building phases, including pre-stressing of construction parts need to be described properly. Figure 3 displays de deformed shape of a concrete viaduct model with the axial stresses being displayed with contours.

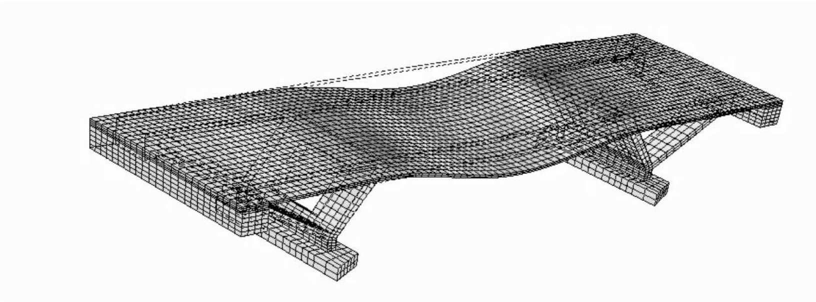

Figure 3: Viaduct model (Courtesy to Dutch Ministry of Public Works)

Buildings

Buildings may have a wide variety of concepts. Historical buildings are composed of masonry, even as small buildings. Large modern buildings in Europe have mostly steel or reinforced concrete framework. For masonry and reinforced concrete the same characteristics apply as was described for transport infrastructure. Other buildings are designed as light-weight structures and comprise typical cable and membrane parts for stabilization of the building. The design of each of these structures has different attention points. Stability and strength are general items. For high rise buildings wind-loadings should be considered. In seismic areas earthquake loadings are essential. Today more and more attention is given to fire and explosion resistance of buildings. Another point is that the use of a building is changed during its life-time and that the strength needs to be reassessed. Reuse of buildings and other facilities not only required reassessment of strength, but it is often necessary to change the layout, i.e. the static system is changed, New loadings are introduced, and it may be necessary to strengthen the structure. Finite Element models for buildings are usually built from scratch in the Finite Element environment. Only recently geometries are defined in CAD programs and interpolated into the Finite Element environment. The major challenges are the easy generation of the model and the definition of appropriate properties for the columns and slabs, taking into account that these are most of the times composites of steel and concrete. Figure 4 shows a finite element model of a apartment building in Rotterdam that has a considerable level of detail. The different colours represent different thickness of the plate and shell elements.

Figure 4: High-rise building model (Montevideo tower in Rotterdam)

2: BUSINESS DRIVERS

The purposes of application of Finite Element Analysis in the Civil Construction industry sector are closely related to the business drivers in the sector:

- *Sustainable and environmentally sound constructions.* After the building boom in the Western world the focus of attention moves from design of new constructions to maintenance and re-assessment of existing constructions. In the Eastern world the building boom is still at full power. Today it is already considered in the design of constructions that the purpose of the building or construction should possibly be adapted during life-time and also scenarios for de-construction are considered. Further, the effects of the (de-)construction to the environment are important factors nowadays. In the near future, it may be required that a complete documentation is provided regarding optimum use of materials and energy plus minimum emissions in the whole construction process.

- *Reduced construction time and construction costs.* Construction costs do not only include the material, tool and labour costs; today contractors are more and more confronted with penalties when construction takes longer than agreed and bonuses can be expected for short construction times. Next to the financial aspects the reduced construction time is also required from a perspective of reducing inconvenience to the environment from the construction.

- *Safety of constructions.* Safety of constructions has several aspects. Recently an increasing interest is noticed for fire-safety of buildings and underground constructions, such as tunnels, can be noticed, as well as for earthquake resistance of buildings and geotechnical constructions.

To the petroleum engineering industry the following business drivers apply:

- *Environmentally sound operations.* National authorities require that environmental effects of mining and production of gas or oil are investigated before licenses for production are provided. Environment effects can be subsidence of the ground-surface with the related increase of ground-water level or tremors which are initiated by the production of minerals. The sealant properties of wells though which the minerals are produced determine risks of unwanted loss of minerals, which may cause damage to the environment.

- *Reduction of risks of failure.* In mining and petroleum production the costs of production facilities are enormous. Serious damage to a well usually means that the complete well is lost, which will break down the operation. Mining accidents cost man-lives. Mining and petroleum industry have great interest to control these risks.

- *Innovative technique should make difficult fields suitable for production.* The ever increasing need for more gas and oil forces the petroleum industry to explore and produce new fields that are difficult to asses. There is also a need to make small petroleum fields viable for development. These fields may be located at great depths (more than 3000m) at which the temperature is around 180 ∞C or at lower depths with very weak heavily faulted overburdens. The risk of failure to wells is high. New techniques need to be developed in order to be successful under these conditions.

3: STATE OF PRACTICE

In this paragraph for the four areas we have defined for the civil construction sector the state of practice will be described specifically and the maturity and priority of the Finite Element technology in relation to the applications will be identified.

Deep Underground

Finite Element Analyses of the deep underground concern, among others, the following applications:

- *Basin and geology modelling:* The purpose of these analyses is to calculate the stress-distribution in rock and shear capacity of faults in the deep underground. These data are important to understand the behaviour of the underground when minerals are produced or predicting risks of earth-movements. In a large area (scale 10-50 kilometres) the geometries of different rock-formations are described as well as slipping faults. By application of a palin-spastic reconstruction the original perfect layered equivalent model are identified. The deformations of the rock at geological timescale are simulated by applying erosion, sedimentation, layer-stressing, such that the original perfect layered model deforms towards the actual strata of rock-layers. The material models are characterized by a non-linear relation between stresses and strains. Because of the extreme time-scales being considered, creep-effects are very important. Large deformation theory should be applied. For this application only the concept of method has been defined and algorithm has been formulated.

- *Oil and gas-reservoir modelling:* The application of Finite Element Modelling to oil and gas-reservoirs concerns two physical aspects: the flow of minerals and water through the porous rock and geo-mechanical aspects. The purpose of these analyses is to find the optimum production scenario for the reservoir and to reduce failure risks. Both aspects interfere: compaction of rock affects the permeability of the rock and flow of gas and oil changes the pore-pressure. For the flow-analysis usually CFD is applied. Finite Element Analysis is applied to simulate the geo mechanical aspects. These models are usually 3-dimensional and comprise rock formations in the reservoir and the environment as well as slipping faults. The models are imported in the Finite Element modeller from geo-modellers. Pore-pressure changes are imported from the flow model. Nonlinear rock compaction models apply. Stress-changes and compaction strains, surface subsidence and fault-slip are calculated. The method has been validated on representative ‘real world’ analysis problems and the implemented functionality, performance and interfacing are complete.

- *Well-modelling:* Well-bores for production of gas and oil from reservoirs are expensive and the risks of failure, especially for fields at later depths or under weak formations, are high. Finite Element Analysis is applied to calculate the stability of boreholes and the risk of failure of wells. The models usually have a 2-dimensional geometry and take nonlinear material behaviour into account. Sometimes heat-flow and gas-oil flow are considered. The rock and cement behaviour is non-linear. The different construction stages should be considered to achieve good results. The application of Finite Element modelling to wells is a robust method, routinely used in industrial production environments.

- Deep tunnel, mining and cavern modelling: Finite Element Analysis, applied to these applications, is mostly restricted to the situation when special conditions are applied such are such as extreme temperature conditions and explosions. This application is very fragmented.

Soil Mechanics

Finite Element Analyses in soil mechanics concern, among others, the following applications:

- *Boring tunnels:* In densely populated areas the need for extension of the travel infrastructure remains. Today the boring of a tunnel underneath buildings is no exception anymore. Possible effects from the tunnel-construction to the environment must be investigated thoroughly before permissions for construction are given. Because the soil behaviour is strongly dependent on the stress-history the different construction phases should be taken into account in the analysis. Models are usually 3-dimensional and simulate the excavation of the tunnel and the construction of the lining. The effect of groundwater should be considered. The method has been validated on representative ‘real world’ analysis problems and the implemented functionality, performance and interfacing are complete.

- *Excavations:* For construction underground structures, or foundations, huge excavations close to existing buildings are created. These excavations may cause changes to the ground-water level or affect the stability of the ground around the excavation. Therefore the stability of the excavation, i.e. the strength of sheet-pile walls, need to be investigated and Finite Element analysis is a very useful tool for doing this. Both 2- and 3-dimensional models are applied. Because the soil behaviour is strongly dependent on the stress-history the different construction phases should be taken into account in the analysis. Sheet-pile wall is modelled with shell-elements, which might be fixed with anchors in the ground. The ground-water flow and load should be considered. The application of Finite Element modelling for excavations is a robust method, routinely used in engineering environments – with adequate software handling.

- *Foundations of buildings and constructions:* The stability of foundations of buildings and constructions brings the behaviour of construction and soil together. There are two major types of foundations: a steel foundation and pile foundations. Steel foundations are concrete slabs directly resting on the soil. These slabs are usually modelled with shell elements. Pile foundations can be modelled either with solid elements or with line-elements. The frictional interaction between pile and soil are of major importance to predict the load carrying capacity of a pile. The same conditions with respect to soil behaviour as described above apply to foundation applications. The stiffness of the construction will usually affect the structure-soil interaction considerably. In most applications, it is sufficient to consider the structure as a linear elastic component in the structure. The method has been validated on representative ‘real world’ analysis problems and the implemented functionality, performance and interfacing are complete, as far as static conditions are applied. The behaviour of foundations under dynamic conditions, such as earthquakes are still strongly in development. For these conditions the method has only be validated on comprehensive representative test-cases.

- *Slope stability:* The assessment of stability of slopes is another area in soil mechanics. The shear resistance of soil is strongly dependent of the fluid pore-pressure in the soil. Slope stability models can be both 2- and 3-dimensional. The same conditions with respect to soil behaviour as described above apply to slope stability applications. The method has been validated on representative ‘real world’ analysis problems and the implemented functionality, performance and interfacing are complete, as far as static conditions are applied. The analysis of slope stability under dynamic conditions, such as earthquakes is still in development. Especially the liquefaction of soil as a result of cyclic loadings is a relevant area of research in this respect. For these conditions the method has only be validated on comprehensive representative test-cases.

Transport Infrastructure

Finite Element Analyses of transport infrastructure concern, among others, the following applications:

- *Design of bridges:* The variety of bridge types is enormous. Traditionally there are steel frame-work bridges. There are suspension bridges with a steel or concrete bridge-deck. More recently the concept of pre-stressed concrete bridges was introduced. On a smaller scale there are the viaducts, which can be masonry constructions or concrete slabs. The design of each of these bridge types has their own attention points. For steel bridges the stability of the global structure and the members and fatigue failure are important attention points. Stability of the bridge deck and the balancing of the pre-stresses in the suspension cables are important for suspension bridges. Stress-distribution in relation to material failure are attention points for pre-stressed concrete bridges. Different loadings apply: the dead weight load, wind load, temperature loads and or course the traffic load. The bridge must be designed to resist the most critical combination of these loads. To investigate the most critical traffic load the idea of influence fields has been developed: This is a linear analysis in which a load from the vehicle to the bridge can be applied on different points of the model (e.g. on all points of the bridge deck) and stresses, cross-section forces and bending moments for each of these loadings in selected result points can be calculated efficiently. The Finite Element models are as diverse as the bridge types. Traditionally simple line models were applied for framework constructions and suspension bridges. Pre-stresses concrete bridges may be modelled with beam or shell elements. Recently also full solid models for concrete bridges and viaducts are defined. For the later the geometries are imported from CAD software. As design-codes do still refer strongly to cross-section forces and bending moments in the construction, rather than to stresses, effective application of solid modelling of bridges requires that these result-items can easily be calculated. The Finite Element Analyses applied to bridge design are usually linear elastic analysis of the system, where many different load-situations are applied to the model. The dynamic frequencies of the linear model and validating these against possible loading frequencies from wind, earthquakes or traffic. The method has been proved to be a robust method and is applied routinely in industrial development environments, and adequate software is widely available.

- *Reassessment of bridges:* Bridges are reassessed because of changed regulations or because of heavier traffic, than was assumed in the design, should be able to pass the bridge. Also reassessment of reinforced concrete bridges occurs as a result of deterioration (steel bar corrosion). If the loading conditions change the question arise what is the limit state loading of the bridge. For a reinforced pre-stressed concrete bridge this is not so easy to answer because the occurrence of cracks does not mean that the limit state is reached. To calculate the limit state a non-linear Finite Element analysis should be done, taking the concrete and steel failure into account. In this analysis the size of the most critical load-combination is increased until the limit state is reached. The non-linear material-models are strongly stress and deformation history dependent. The steel reinforcements in the concrete should be taken into account explicitly, because their failure characteristics are different than the plain concrete. Therefore the different building phases and loading history must be taken into account. These application of Finite Element analysis has been validated on representative real world analysis problems and the specific functionality has been implemented in software whereas performance and interfacing is complete.

- *Reassessment of tunnel-constructions:* Because in recent years a number of accidents in tunnels caused fire and resulted in great damage to the construction, tunnel constructions in Europe are being reassessed with respect to fire-safety. There are still many uncertain factors, such as the heat development and the material behaviour of concrete under extreme temperature conditions. In research projects directed to increase fire-safety of tunnels, Finite Element analysis of the strength of the tunnel construction, is considered as an important tool. The concept and application of the method have been formulated.

Buildings

Finite Element Analyses of buildings concern, among others, the following applications:

- *Design and reassessment of high-rise buildings:* The running match for construction of the tallest building continues to write new records. Nowadays more new high-rise buildings are constructed in the Eastern than in the Western part of the world. In the design and reassessment of high-rise buildings the Finite Element analysis has established its place. The models comprise usually a combination of shell, membrane and beam elements, for modelling floors, walls and columns. In the design the dead-weight of the building, wind loading, in some areas earth-quake resistance, operational loads are considered. The models contain many elements. Usually only linear-elastic and Eigen-frequency analysis are performed. Very recently the need for investigating the fire-resistance of a building has increased very strongly. For a fire-safety analysis the heat transfer of the building must be calculated and the dependency of material characteristics with temperature must be accounted for. Therefore a transient analysis is required. The application of Finite Element analysis to high-rise buildings considering the traditional design loads is a robust method which is routinely used in industrial environments and adequate software is available for that. For design or reassessment of a high-rise building with respect to fire-safety, the performance of Finite Element analysis has been validated on comprehensive test-cases and the tools are expected to improve for this application shortly.

- *Design of utility buildings:* Utility buildings must be cheap and have a shorter life-expectation than other buildings. These buildings usually are composed of a steel framework with light-weight covers. Finite Element models for design of these building usually are composed of beam and membrane elements. Linear elastic and Eigen-frequency analysis are performed. The application of Finite Element analysis to utility buildings considering the traditional design loads is a robust method which is routinely used in industrial environments and adequate software is available.

- *Light-weight and ‘designer’ constructions:* There will always be a need for unusual designs for buildings. Unusual can be with respect to materials applied or with respect to shape of the construction. Some architects have specialized in design of so-called ‘blob’ structures, which are characterized by large multidirectional curved surfaces. Traditional construction rules can not always be applied, but Finite Element analysis offers help. Interfacing with CAD is very important even as the modelling of construction details. The models are usually defined by beam and curved shell elements. Linear elastic and Eigen-frequency analysis are performed. The application of Finite Element analysis to light-weight and ‘designer’ constructions has been demonstrated on ‘real world’ analysis problems. In principle the required functionality has been implemented in the software but need to be developed further before it will be common practice.

4: GENERAL TECHNOLOGY NEEDS AND AREAS FOR RESEARCH

From the different sessions with industry representatives which have taken place in the FENET project the following general technology needs and areas for research have been identified with respect civil construction industry sector:

- *Pre-processors for 3-dimensional geotechnical analysis:* The definition of 3-dimensional Finite Element models geo-technical applications is an elaborate and difficult task in most general purpose programs. This is because variations of thickness in ground-layers can not easily be defined; constructions are modelled with shells and soil with solids and in order to model the frictional slipping between soil and construction special interface elements must be applied, which are not available in most general purpose programs; there are no functions available for defining the ground water level.

- *Pre-processing of reinforced concrete structures:* For non-linear stress analysis the steel reinforcement and the concrete embedment must be defined in the Finite Element model explicitly. Usually the reinforcement bar is defined with cable elements, whereas the concrete is modelled with solids. Most programs require that the nodes of the solid elements are matching with the nodes of the cable elements. This is a very severe condition for pre-processing reinforced concrete structures. Some suppliers offer the capability to define the reinforcement grid independent of the mesh-distribution of the concrete and calculate the embedment of the steel reinforcement to the concrete elements automatically.

- *Concrete models for cracking and compression:* Although there are many cracking models available, the application of these models requires some expertise. Further, when the structure starts cracking the load carrying capacity may reduce strongly and to overcome this special solution procedures are required. Also there modelling of the compressive behaviour of concrete may be improved, especially for 3-dimensional applications.
- *Soil behaviour under cyclic loading:* The constitutive models available for soil are mostly based on non-linear elasticity theory or on elasto-plastic theory. Soil behaves essentially nonlinear at both loading and unloading conditions. The present elastic and elasto-plastic models are good for monotonic loading conditions, but have short-comings for modelling cyclic loading conditions.

- *Interaction of different physical aspects:* Calculation of the strength of the construction is traditionally the main purpose for application of Finite Element analysis in the design of civil constructions. A number of examples have been identified in this paper in which the mechanical behaviour of the construction is affected by other complex physical phenomena, such as fire and wind loadings. Wind and fire analysis are usually done in a CFD environment. Easy import of CFD results into the FEM environment is expected to be an important development for the next years in order to achieve more accurate simulations.

- *Stochastic models:* Loadings in civil constructions and material properties soil are only two of the many uncertain factors in civil constructions the design engineer has to deal with. A stochastic approach of Finite Element analysis, in which model parameters can be stochastic and for which limit states for results can be defined, could calculate the chance that limit-states are reached as well as the failure mode, automatically. Such a tool would be a very helpful for the design-engineer to establish risks of failure of a construction.