Amsterdam University
of Applied Sciences

INAUGURAL LECTURE

Structural Safety in the Netherlands

Problem, analysis and solution

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Professor of Structural Safety

Creating Tomorrow

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To the Rector, University Board Members, Professionals, Students, Colleagues and Family

Through this public lecture, I accept the position of Professor of Structural Safety at Amsterdam University of Applied Sciences (AUAS). This appointment is a great honour and affords me the opportunity to lead a national lectorate in cooperation with the national concrete association BV and the national steel association BmS, in addition to their corresponding master's programmes in structural design.

As with this inaugural lecture, all educational materials of this lectorate, as textbook materials and presentation notes, are in English for international communication and research. The oral presentations, however, are in the audience's native Dutch for profound understanding.

1 Structural (un)safety in the Netherlands

1.1 *Structural failures*

In the Netherlands, there has been a notable number of structural failures over the last decades. For example, roofs and parking decks have collapsed while in use. Buildings have also collapsed, mostly during construction. Some of the most publicised structural failures include:

- Theatre Het Park, Hoorn (2001). Collapse of the theatre tower during construction due to a combination of engineering and construction errors.
- Hotel Van der Valk, Tiel (2002). Parking deck collapse caused by a lateral torsional instability and subsequent horizontal displacement of the supporting beams.
- Bos en Lommerplein, Amsterdam (2006). Near-collapse of supporting parking garage beneath a residential complex because of missing concrete reinforcement.
- Stadium De Grolsch Veste, Enschede (2011). Roof collapse during construction due to a loading of the incomplete stabilised roof structure.
- Queen Juliana Bridge, Alphen aan den Rijn (2015). Pontoon-based crane collapse during construction as a result of severe shortcomings in construction engineering and management.
- Eindhoven Airport (2017). Floor collapse due to an unusual orientation of wide-slab flooring in combination with insufficient overlapping of the reinforcement splices.
- AFAS Stadium, Alkmaar (2019). Roof collapse caused by engineering errors with respect to wind loading and weld strength of the roof structure.

1.2 *Structural safety codes of practice*

Eurocode (NEN-ISO 6707-1, 2017) defines *structural safety* as the capacity of a structure to resist all action(s), as well as specified accidental phenomena during construction work and in anticipated use. Eurocode EN 1990 (NEN-EN 1990, 2019) defines *reliability* as the ability of a structure or a structural member to fulfil the specified requirements throughout the working life for which it has been designed. There are four dimensions of structural reliability: safety, serviceability, durability, and robustness. The semi-probabilistic level I calculations in the material-related Eurocodes are based on the assumption that an element is reliable if a certain margin is present between the representative values of load effect and resistance (fig. 1).

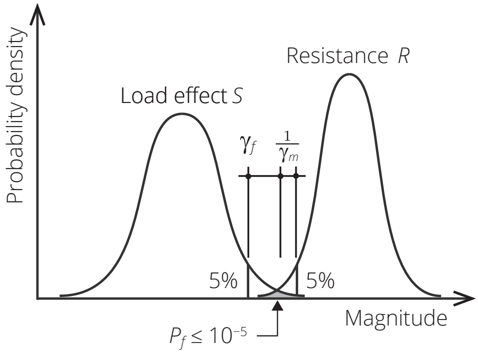

Figure 1. Structural safety Eurocode.

The representative value of load effect S has a 5% probability of overshooting; the representative value of resistance R has a 5% probability of undershooting. The use of probability of exceedance instead of mean values incorporates the influence of probability distribution. The resistance is the capacity of a structure to resist a load effect. The verification implies that the resistance R has to be greater than or equal to the load effect S. The risk of failure when $R < S$ should be sufficiently low.

When there is no margin between the representative values of S and R, the probability of failure is approximately $P_f \leq 10^{-1}$, which is sufficient for the Serviceability Limit State (SLS). However, for the Ultimate Limit State (ULS) this probability of failure $P_f \leq 10^{-1}$ is entirely insufficient and should be upgraded to $P_f \leq 10^{-5}$. The corresponding margin between the representative values of S and R can be obtained by global partial factors γ_f and γ_m for load effect and resistance, respectively. The verification of the safety is then based on the following equation:

$$S \cdot \gamma_f \leq \frac{R}{\gamma_m}$$

These partial factors cover stochastic variability, which is related to uncertainties in loads, materials, geometry, and calculation models. However, stochastic variability does not include gross human errors.

1.3 Actual structural safety

The actual structural safety in the Netherlands with a probability of failure over the last decades below $P_f \leq 10^{-6}$ easily meets the required structural safety level of the codes of practice with a probability of failure of about $P_f \leq 10^{-5}$. However, actual safety ($P_f \leq 10^{-6}$) is not a subset of the regulated safety ($P_f \leq 10^{-5}$) as substantiated by Terwel (2014):

An extensive study of structural failures in the Netherlands has shown that the number of fatalities caused by these structural failures remains within acceptable limits, although a high impact-low probability disaster did not occur in the observed time interval. This study also shows that about 90% of the failures are caused by human error, although human behaviour is not included in the Eurocode's probabilistic calculation. It seems paradoxical that the individual risk remains within acceptable limits, although the main factor, human error, is not included in the calculation approach. This is because the actual strength of structures is often greater than the calculated strength due to redundancy.

1.4 Professionals' lack of insight

Several recent disasters have been investigated by the Inspectorate for Housing, Spatial Planning and the Environment, research organisations, the Dutch Safety Board, university professors, expertise firms, and special committees of enquiry. These investigations have found that a disaster rarely has a single identifiable cause. Rather, a disaster is the result of constellation of interconnected factors and circumstances that are inherent in the building process. All these factors and circumstances influence the structural safety of a building. Many failures, however, originate in the design phase.

Structural collapses in the Netherlands appear to result from the lack of supervision during all project phases and professionals' lack of insight into structural engineering, as recorded in the problem statement "Castle or House of Cards" (Spekkink, 2009) under the management of the Ministry of Housing, Spatial Planning and the Environment.

This problem statement addresses some concerns of the Ministry of Housing, Spatial Planning and the Environment:

- Many in the construction industry realise that the level of skill not only among structural engineers, but also among other professionals, is declining.
- University professors are noticing a general erosion of knowledge and command of applied mechanics, the mainstay of the structural engineering profession.
- The “black box” character of calculation software will further diminish people’s understanding of the subject.

Eight organisations, including the Inspectorate for Housing, Spatial Planning and the Environment, the Concrete Association, and structural engineers and builders’ organisations published the “Compendium for a Structural Safety Strategy” (Spekkink, 2011). This compendium contains a detailed description of how structural safety can be guaranteed throughout the design and building process and what roles the participants in the building process can play with regard to structural safety. Since 2018 this compendium has evolved into a national platform for structural safety, KennisPortaal Constructieve Veiligheid (KPCV) (www.kpcv.nl).

2 Historical perspective

2.1 Developments in professional structural engineering

With the increasing complexity of structures and their corresponding design, master builders of ancient times inevitably evolved into teams of specialists (fig. 2):

- *Homo universalis* (section 2.2): master builder with expertise in architectural, structural, and construction engineering. This master builder is depicted as Leonardo Da Vinci's "Vitruvian Man", based on the correlations of ideal human proportions with geometry described by the ancient Roman architect Marcus Vitruvius Pollio (2003).
- Expanding depth and breath (section 2.3): structural engineering as a separate formalised discipline.
- Ongoing and expanding depth and breath (section 2.4): specialisations within the professional field of structural engineering.

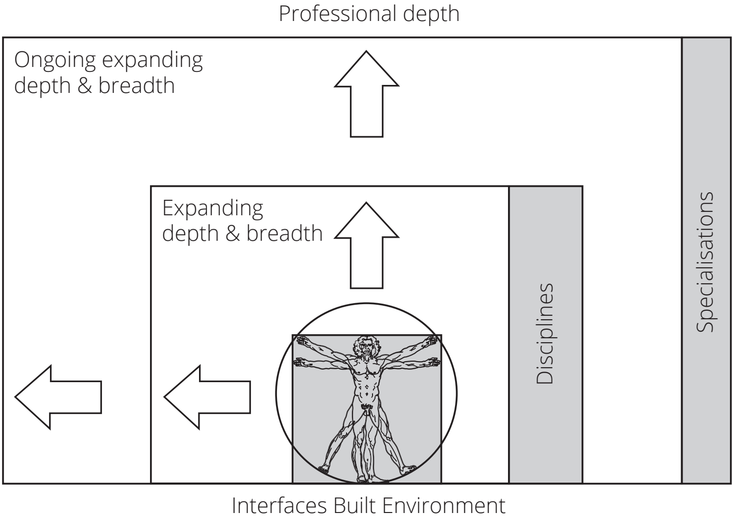

Figure 2. Expanding depth and breadth.

2.2 *Homo universalis*

Structural engineering began with the construction of the first human-made structures. Throughout ancient and medieval history all architectural, structural and construction design was carried out by a single person – often a master builder. Structural comprehension was extremely limited and almost entirely empirical. The physical sciences underlying structural engineering began to be understood during the Renaissance of the late 15th century. It was then that architectural, structural, and construction design evolved into a deeper and more controllable kind of knowledge. Still, it remained in the hands of one person, known as *Homo universalis*.

The Latin term *Homo universalis* can be translated as “universal person”, someone with a broad knowledge of several fields and with proficiency or accomplishments in some. Two of the universal persons who lived during the Renaissance were Leonardo da Vinci and Michelangelo. Until the 19th century, only one person was needed to integrally oversee the design, a generalist with expertise in architectural, structural, and construction engineering. The term *generalist* is used to contrast this scope to knowledge to the narrower scope of the *specialist*.

2.3 *Expanding depth and breadth*

With the development of specialised knowledge of structural theories, which emerged during the industrial revolution in the late 19th century, structural engineering emerged as a more defined and formalised discipline. The knowledge of materials, technologies, and construction methods was increasing and structures became more complex. Due to the limited ability of each professional to comprehend everything about the field of building engineering, the field was inevitably divided into separate disciplines such as architecture, structural engineering, and construction engineering.

The modern structural engineer can rely on a long history of validation of theoretical approaches that have produced extensive knowledge databases such as applied mechanics-based structural analyses, previous designs, design rules, design codes of practice, and research. To complete any project, it now takes a team of structural engineers working with mechanical, geotechnical, electrical, and civil engineers, and urban planners and architects.

2.4 Ongoing and expanding depth and breadth

The volume of knowledge of materials, technologies and building methods continues to increase enormously. Furthermore, there is a tendency away from the explicitly deemed to satisfy provisions towards more implicit performance-based contracting. This requires corresponding expertise and more specialisation than ever. Within the field of structural engineering alone there is so much expertise that no single structural engineer can master it, resulting in specialisations such as geotechnical engineering, pre-stressed concrete engineering, finite elements engineering, and bridge engineering.

Numerous sophisticated high-end automated design tools support the daily practice of the present-day professional structural engineer. In spite of, or perhaps just because of these design tools, today's young structural engineers lack a fundamental knowledge of structural behaviour, and a sense of and insight into the conceptual design process and its related interfaces. In short, they do not understand the basic design parameters of form, material, and dimension.

3 Solution approach

3.1 *Problems, causes and effects*

The problem of structural unsafety in the Netherlands has many causes. This inaugural lecture will discuss the causes and effects of professionals' lack of insight into structural engineering, as noted in the problem statement (Spekkink, 2009). There are two separate problems:

1. Lack of insight into structural performance on the micro level: human error and inadequacy of people working on building projects.
2. Lack of insight into conceptual structural design on the macro level: problems relating to the structure and culture of the building sector.

The lack of insight into structural performance is believed to have been caused by the erosion of knowledge of applied mechanics, the mainstay of the structural engineering profession. The extensive use of calculation software, essentially a "black box", has diminished the understanding of structural performance. Conversely, the lack of insight into conceptual structural design is believed to have been caused partly by the growing number and complexity of interfaces with other disciplines and corresponding collaboration processes, and partly by an increasing complexity of the Design, Build, Finance, Operate, Transfer (DBFOT) model, the Value for Money (VfM) model and other contractual models.

These causes can have considerable effects on both safety and costs. The lack of insight and especially the improper use of advanced computer programs can jeopardise structural safety. Furthermore, an uncontrolled design process can bring about insufficient performance/cost optimisation and high failure costs. Besides a tendency for excessive numerous functional requirements, process control and reliability of a tender build-up is obviously endangered by the professionals' lack of insight.

3.2 *An interface control approach*

The two problems noted in the previous section are depicted in figure 3:

1. Lack of insight into structural performance on micro level: present-day understanding of structural performance is characterised by a constant expansion of complex analysis tools, without an adequate control of the interface between applied mechanics and the material applications.
2. Lack of insight into conceptual structural design on macro level: present-day conceptual structural design is characterised by a constant expansion of requirements, related interfaces, and collaboration models, without an adequate organisation of the possibilities created by controlling the interface between the body of knowledge of the built environment and the demands of the customer.

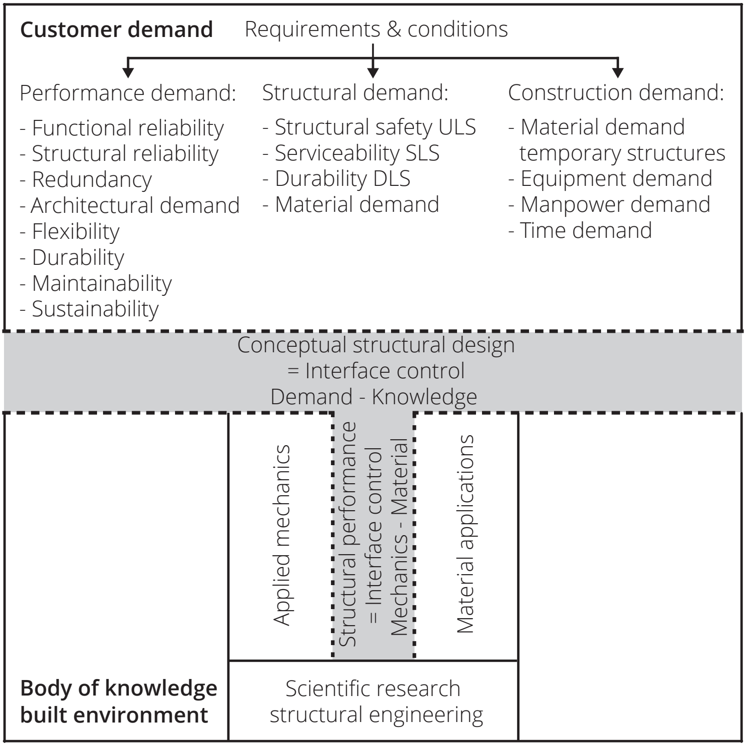

Figure 3. Structural design as an interface control approach.

3.3 A need for control on system level

As with many complex design problems, the standard planning and control mode is not enough to guarantee a solution. This formalistic, bookkeeping-like approach supports only basic process control. With regard to the quality of the design solution even planning and control with elaborate procedures and explicit supervision protocols – as proposed in the joint Compendium for a Structural Safety Strategy (Spekkink, 2011) – merely gives an illusion of control and reliability. Furthermore, elaborate process control with too many regulations and control systems stifles creativity, progress and cooperation. Especially process control and reliability of a conceptual design – and in particular the preceding tender build-up – is endangered by a present-day tendency towards excessive numerous functional requirements and control procedures.

By the same token, effective proven design tools such as systems engineering and BIM do offer control and clarity to open the way to creativity, progress and cooperation. Individual components of these applications, such as decomposition techniques and applied mechanics-based calculation routines can be very useful for a solution approach on conceptual structural design.

3.4 Shift from calculating to modelling

As a result of modern sophisticated automated design the field of practice shifts from calculating/checking to modelling/designing. This shift requires a fundamental understanding of modelling in combination with research skills:

1. Modelling of load distribution in complex structures and modelling of material behaviour of new structural materials, new applications of existing materials and new production techniques.
2. Research skills as an effective and efficient problem-solving tool for complex structural problems.

For the professional field of practice, research skills can subsequently be divided into universal systematic thinking and applied systems thinking:

2a. Systematic thinking based on the scientific research method about problem definition, research framework, hypothesis, validation, and conclusion.
2b. Systems thinking as a holistic approach from the whole to the part and from coarse to fine, regarding complex interfaces, structural integrity, load distribution, and failure mechanisms.

4 Lectorate Structural Safety

4.1 Three pillars of future-proof structural design

In conclusion, the field of practice shift from calculating/checking to modelling/designing requires the following three pillars for a future-proof structural design as shown in figure 4: universal systematic thinking, applied systems thinking, and applied mechanics-based modelling.

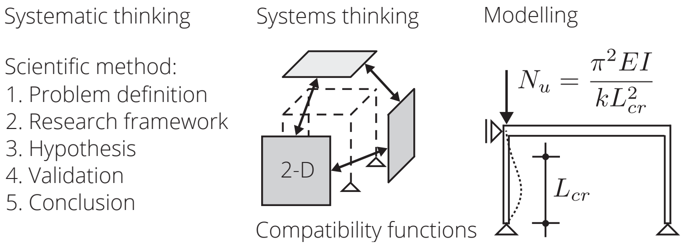

Figure 4. Three pillars of future-proof structural design.

Systematic thinking

Scientific research has to comply with the basic principles of the scientific method. The essence of the scientific method is to test a hypothesis, and replication of this testing should get the same response; this response can be measured and recorded. The following five steps can outline the scientific method:

1. State a problem and define a corresponding research question.
2. Investigate what is already known and structure the solution finding by means of a research framework.
3. Formulate a hypothesis as a solution to the problem.
4. Test the hypothesis and analyse the results on whether to accept, adjust, or reject the hypothesis.
5. Conclude, with recommendations for further research, and publish the results.

The underlying goal or purpose of science to society and individuals is to produce useful models of reality. To achieve this, one can form hypotheses based on observations of reality. By analysing a number of related hypotheses, scientists can formulate general theories. These theories benefit society and individuals who make use of them.

Systems thinking

Systems thinking is about patterns and relationships to describe how things interact and understand why systems behave the way they do. Systems thinking consists of various perspectives or interpretations of reality. Present-day system theories development aims at tools and methods to comprehend and manage the complexity of the total system life cycle. Modern developments include performance-based design, multidimensional modelling management, and quantitative risk management.

Because of the multitude of parameters and the complexity of interrelations, a workable numerical power-based design method seems far in the future. In the long run, however, the ideal artificial intelligent expert system is surely a possibility. The time gap between today' needs and tomorrow's artificial intelligence will probably be large enough to justify a simpler applied system thinking for conceptual structural design.

Modelling

Due to the complexity of material behaviour, structural analysis depends on abstract representations of the actual structure. Modelling an abstraction has its limitations. For a reliable application of structural modelling, understanding these limitations is paramount; for example, when shear deformation is dominant. To perform an accurate analysis, the structural engineer must obtain information about structural loads, geometry, material properties and support conditions. The results of such an analysis typically include support reactions, member forces, and displacements. This information is then compared to criteria that indicate the conditions of failure.

Manual calculations of the structural action are based on analytical formulations that apply mostly to simple linear-elastic and ideal-plastic analysis models.

Computer calculations of the structural action are generally based on the finite element method, including the most commonly used displacement method. It is a numerical method generated by theories of mechanics and is applicable to structures of arbitrary size and complexity. The finite element method also helps in producing stiffness and strength visualisations. Regardless of approach, the formulation is based on the same three relations of equilibrium, constitutive – stress-strain relationship, and compatibility – strength and stiffness transfer between elements. The solutions are approximate when any of these relations are only approximately satisfied, or an approximation of reality.

4.2 National collaboration

In response to modern societal and technological developments the national concrete association BV, the national steel association BmS and the Amsterdam University of Applied Science – including their corresponding professional master's programmes in structural design – established a four-year national lectorate, "Structural Safety" starting 1 September 2019. This lectorate is a starting point for a close collaboration among the three professional master's programmes, including a linkage with the Dutch equivalent of the international Chartered Engineer register.

At the request of and in collaboration with the field of practice, the following three professional master's programmes in structural design fulfil the national educational needs:

- National concrete association BV: The structural design programme BV for and by the concrete industry focuses on the structural material concrete and corresponding building and civil engineering structures.
- National steel association BmS: The structural design programme BmS for and by the steel industry emphasises the structural material steel and corresponding building and civil engineering structures.
- Amsterdam University of Applied Science: The Master's in Structural Engineering programme instills a profound understanding of the structural behaviour of common building structures and common structural materials.

In analogy with academic higher education, this lectorate of professional higher education focusses on a combination of practice-based research and educational material for the corresponding programmes, resulting in relevant research outcomes, innovative educational material, and professionalisation of educational staff.

These research outcomes and educational material are open access available at the website of the lectorate (www.bvbms.nl). The research will be published in national trade journals.

4.3 Core tasks of the lectorate

With regard to structural safety, the lectorate's primary objective is to contribute to the national concrete association BV, the national steel association BmS, and the Amsterdam University of Applied Science – including their corresponding professional master's programmes in structural design – as major knowledge-based institutions for the field of practice:

1. Higher education development: Innovative educational material for an effective and efficient approach to design with a fundamental understanding of modelling in combination with research skills as universal systematic and applied systems thinking.
2. Practice-based research: Valorisation of scientific research on sustainable structural materials and sustainable structural systems. The basic research budget of the lectorate consists of the three master's thesis research programmes and amounts 1 up to 2 million euro per year.

Lecturers act as mentors and thesis examiners, and incorporate relevant research outcomes into their curricula. In this way research and education are linked, resulting in innovative education programmes and the professionalisation of educational staff.

5 Education development programme

5.1 *Professional higher education*

In the hands of experienced conceptual designers, sophisticated high-end automated structural analysis tools can contribute to, for instance, an exploratory analysis of complex structural action. In the hands of inexperienced young professionals, however, the conceptual design capabilities of these tools diminish. Computerised designing with insufficient insight – particularly in the conceptual design phase – is a dangerous operation both from a safety and an economic point of view.

With the expansion of high-end automated design tools, the simplification and decomposition techniques used by experienced structural engineers are disappearing from practice training and higher education programmes. University professors are noticing a general erosion of knowledge and skills of applied mechanics, the mainstay of the structural engineering profession (Spekkink, 2009). Furthermore, education about structural design in general, and conceptual structural design in particular, lacks an integral educational programme and corresponding emphasis on the interfaces among disciplines.

5.2 *Decomposition of complex systems*

The concerning education development programme 2019-2023 is the follow-up of a previous academic study on the complex problem-solving process of structural conceptual design (Horikx, 2017). Particularly the complexity of the interdisciplinary interfaces makes both the design process and the overall behaviour of a structural system complex. To analyse such a complex system, Kickert's (1979) decomposition approach, refined by De Ridder (1994) can be applied: physical, process, and aspect decomposition.

Physical decomposition

This way of decomposition follows the physical parts of a system. Often, it is a very natural way of decomposition because we easily "see" all the physical parts. The completeness criterion of physical parts is easy to check; when we have processed all physical parts, we have the whole system. In addition, the failure of physical parts can be located naturally and described more clearly.

The actual physical decomposition of a structural system is elaborated in section 5.3.

Process decomposition

When looking at chemical plants or production plants, a recipe or a production plan forms the essence of their functionality. In this case, process decomposition is most natural and allows for the most effective abstractions. The focus of process decomposition lies in the form of causal chains in the system. Section 5.4 elaborates the actual process decomposition of conceptual structural design into phases.

Aspect decomposition

The interaction among aspect parts of the built environment – functionality, costs, aesthetics, strength, redundancy, constructability, flexibility, durability, maintainability, and sustainability – becomes complex when disciplinary boundaries are crossed. Although an integral conceptual design is a highly cyclical process, the complexity lies in its interdisciplinary aspects. As a result of this complexity of the interdisciplinary interfaces, the loss of information at the borders of the partitioned disciplines will be unacceptably large and decomposition cannot be effective. Then concurrent engineering of all system theories in general, and decomposition-based methods in particular, is a solution. Its use and preconditions are described in chapter 7.

5.3 Physical decomposition

The characterisation of a problem is part of its solution. However, the characterisation of a bridge, barrier or building is nearly impossible due to the variety and complexity of structural forms. Characterisation of individual forms in terms of the capacity to bear and resist, and with regard to the interfaces with the built environment, appears feasible. The load distribution on the system, through the subsystems into the elements can best be determined on a subsystem level with design approximations of the load distribution in basic structural forms.

Possible three-dimensional system effects have to be incorporated into the load distribution of the subsystem. The result is an approximate determination of the forces in each element. With these forces, the dimensions of the individual elements can be determined by means of design approximations of the load-carrying capacity of elements with regard to sectional strength and element stability. Figure 5 shows the dimensioning routine.

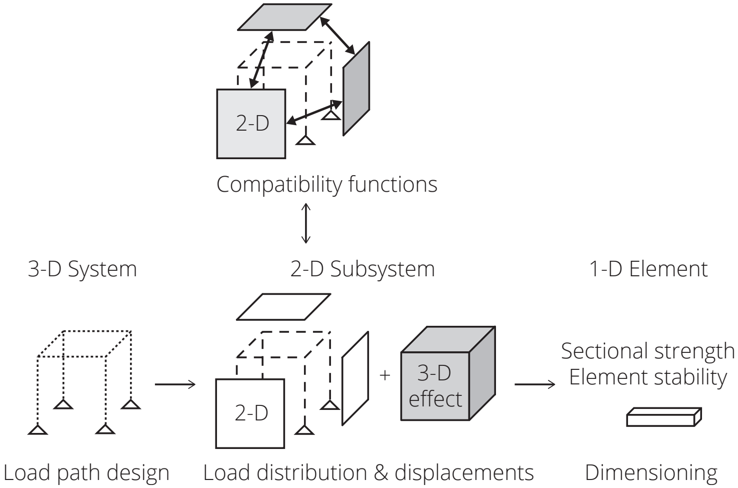

Figure 5. Dimensioning routine.

Comprehending possible three-dimensional load distribution effects in an early stage of the conceptual design process requires retention of three-dimensional effects during decomposition of the three-dimensional system in two-dimensional subsystems. This system decomposition can be done either by defining the compatibility functions between the subsystems or by separating the three-dimensional effect (fig. 5). Defining the compatibility functions to such an extent that they can be used for a neat quantification of the three-dimensional load distribution is too complex and time-consuming for a conceptual dimensioning. Therefore, qualification and approximate quantification of a separated three-dimensional effect is the remaining feasible option.

5.4 Process decomposition

Independent of life cycle phase, complexity of design, and contractual commitments, the structural engineering practice can be reduce to a cycle of creation, optimisation, and specification. The structural design process can be characterised by two simultaneous processes:

- The specification of the structural form from approximate to accurate.
- The composition or decomposition of the structural form, from system to element.

These two processes can be visualised in a two-dimensional matrix (fig. 6). On the horizontal axis, the phases of specification are arranged from creation of the system outline, via optimisation of the structural action, to dimensioning and specification. On the vertical axis, the phases of decomposition of the structural form are arranged from a three-dimensional system, to a two-dimensional subsystem, to a one-dimensional element.

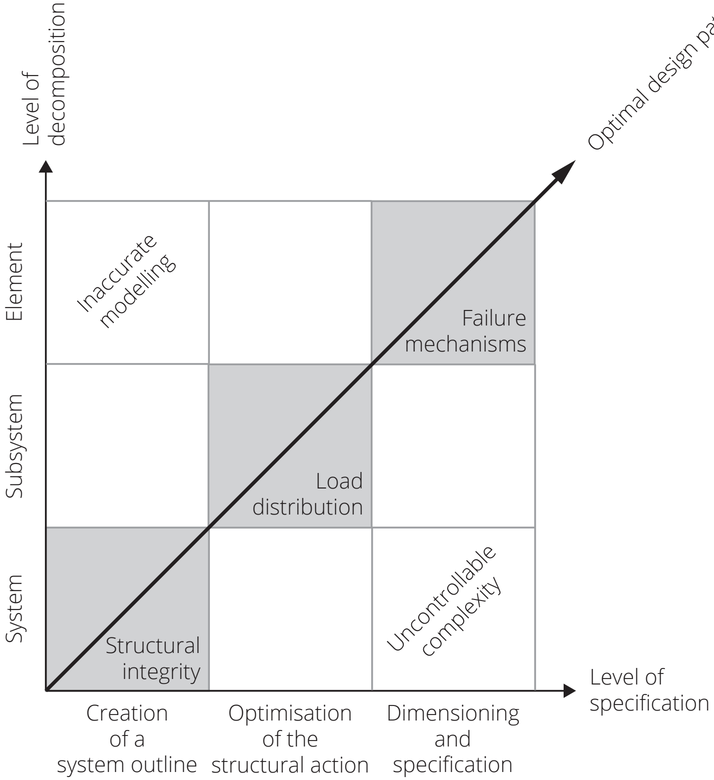

Figure 6. Fundamental structural design path.

Complex structures can be analysed “from system to element” and “from approximate to accurate”. The corresponding design path is directed by this combination of breadth and depth. For an effective convergence, this combination has to be balanced. The design path follows the dimensioning routine from structural integrity, via load distribution, to failure mechanisms:

- Structural integrity: Three-dimensional system design and decomposition in subsystems.
- Load distribution: Distribution of the actions within the subsystem on element level.
- Failure mechanisms: Distributed actions can be resisted by materialising the elements.

Outside the boundaries of this design path, inaccurate modelling or uncontrollable complexity can be found.

To solve a complex structural design problem, a cyclic design process is required. Every cycle goes through the phases of creation, optimisation, and specification. The concept is then reviewed with respect to the functional requirements, and a performance/cost optimisation over the life cycle. When the concept is found to be insufficient, a new cycle is appropriate.

In the process of materialisation from requirements to construction, ongoing design and check activities can influence foregoing activities with regard to choice of geometry, material, and matching dimensions. The number of cycles depends on the strength of the initial idea, and on the improvements one chooses to make; intelligent improvements will reduce the length of the cyclic design process. The cyclic design process evolves to produce at least a performance-based solution if not the most successful outcome. In an effective converging process, the number of optimisation loops will diminish in the course of specification.

6 Practice-based research programme

6.1 *Practice-based research*

Within the triangle of field of practice, practice-based research, and professional higher education, the three components are interconnected:

1. Field of practice: Collect future-proof and mostly long-term research questions from the field of practice and from local and national government organisations.
2. Practice-based research: Execute research projects and publish the results with open access for the field of practice, educational programmes and for continued in-depth research.
3. Professional higher education: Incorporate research outcomes into the professional master's programme in structural design and particularly in the material-related programme modules.

The conversion of practice-based research outcomes into innovative educational material about new structural materials, new applications of structural materials, and new production techniques, takes place in the material-related programme modules. Because these new material applications are not covered by the validity area of the Eurocodes, the background documents of these Eurocodes are appropriate educational material, supplemented with practice-based research outcomes. For this conversion, a classification based on analogous material properties can be effective: ductile (steel and aluminium), brittle (masonry and glass), anisotropic (timber and synthetic material), and hybrid (reinforced concrete and reinforced synthetic material).

6.2 *Sustainable structural materials*

The 2019-2023 practice-based research programme on sustainable structural materials typically include new structural materials such as conventional synthetic or biosynthetic materials and new applications of structural materials with regard to high strength and reinforcement structural materials. Furthermore, new production techniques such as three-dimensional printing of structural materials as concrete, steel, and fibre-reinforced composites are researched. Generative design combined with three-dimensional printing offer an unprecedented organic freedom of form, material efficiency, and short lead times.

Design approximations of strength and stiffness of common structural materials are widely accessible through textbooks and design codes of practice. Approximated behaviour and strength of new structural materials, however, have to be modelled carefully. Especially brittle material behaviour, and corresponding approximate conceptual modelling, is not widely accessible. Brittle material behaviour requires far more in-depth modelling to detect and prevent high-peak stresses with consequent progressive tearing failures. In general, the relationship between the degree of ductility – quantified by the length of the ductile or plastic zone – and the required corresponding degree of in-depth modelling, has to be researched. In particular, the behaviour of such structural materials and an effective approximate modelling for conceptual design should become available.

6.3 Sustainable structural systems

The 2019-2023 practice-based research programme on sustainable structural systems typically include the industrial, flexible and demountable building concept, robustness by load-path redundant and earthquake-resistant designing, and national bridge renovation and urban quay wall renovation programmes, preferably utilising sustainable structural materials and production techniques.

The practical relevance is often researched by redesigning a structure with the emphasis on circular building, comparing flexibility, production, service life, and maintenance, resulting in sustainability on the basis of, for example, CO_2 emission. Whereas production costs are less relevant for such innovations, initially high costs can become profitable after large-scale production and use.

7 Conclusion

7.1 Structural safety

In the Netherlands, the structural failures over the last decades can be traced to the following professional levels:

- Contracting authority: Insufficient performance management, among others due to tendering on lowest price.
- Building industry: Insufficient risk management, among others due to complex organisation of mostly one-time products.
- Structural engineer: Insufficient modelling management, among others due to the shift from calculating/checking to modelling/designing.

The insufficient performance and risk management, which occur on macro level concerning the structure and culture of the building sector, are to be solved by contracting authorities and the building industry, supported by the national platform for structural safety KennisPortaal Constructieve Veiligheid (KPCV).

The insufficient modelling management, which occurs on micro level, is the core task of the “Structural Safety” lectorate, resulting in the development of missing educational material about a fundamental understanding of modelling and missing practice-based research on the application and corresponding modelling of new sustainable structural materials and systems.

7.2 Life cycle optimisation

Design plays an essential part in the creation of the built environment. The interdisciplinary design of the built environment consists of cyclic design processes, culminating in a physical system. The ISO 9000 (2015) defines a *system* as a “set of interrelated or interacting elements”; a *process* is a “set of interrelated or interacting activities that use inputs to deliver an intended result”.

The traditional approach to complexity is to reduce or constrain it. Typically, this involves decomposition techniques as discussed in section 5.2. Physical decomposition is elaborated in section 5.3 and process decomposition in section 5.4.

Unsolved aspect decomposition however, concerning the numerous aspect parts of the built environment, can be classified as physical or non-physical. For example architectural demands can include non-physical elements, as aesthetics can neither be classified as physical, nor as a process. Particularly the interacting of these non-physical elements such as aesthetics, load paths, and constructability becomes complex when the corresponding traditional disciplinary boundaries have to be crossed. It is important to study how the design is organised in practice, and especially the ways in which designers with different disciplinary expertise are able to work together, collaboratively in teams. A motivation of these studies is not only to improve design processes but also the designed system itself.

On the object level, the interfaces of the object-related structural engineering with the other object-related disciplines are within the system functionality of the object and can be substantiated as follows:

- Property management: The performance/cost ratio is the main driver for the overall optimisation of conceptual design. Regarding life cycle costs, maintenance, and management are gaining in importance, and are therefore substantial input for conceptual design.
- Installation engineering: The main ducts of air conditioning systems have the same scale as girders and are preferably designed in parallel. Smaller installations normally have minimal to no influence on structural dimensioning.
- Architectural engineering: Architecture is a conscious creation of utilitarian space and construction of materials in such a way that the whole is both technically and aesthetically satisfying. Creation of utilitarian space with materialised forms is a main influential design interface with the structural form.
- Construction engineering: The feasibility of the execution focuses on avoiding unnecessary complexity, on influences on dimensions and tolerances, and on possible choices among alternatives.

On the environmental level, the interfaces with the object-related structural engineering consist of geometrical and loading constraints such as free space profiles, road cross sections, traffic loads, and hydraulic loads. So for the determination of shared knowledge with respect to conceptual structural design, the emphasis is on the object-related disciplines. Because of the complexity of the interdisciplinary interfaces between these disciplines, concurrent engineering is an appropriate solution. After all, the concurrent engineering approach provides a collaborative, co-operative, collective and simultaneous engineering working environment, based on the five key elements: process, multidisciplinary team, integrated design model, facility, and software infrastructure.

For effective optimisation over the life cycle of a structure and the reduction of present-day substantial failure costs, concurrent engineering between the interrelated disciplines of property management, installation engineering, structural engineering, architectural engineering, and construction engineering is an essential prerequisite. For this, production and subsequent sharing of knowledge bases per discipline have to be established. Following the education development of this lectorate, the fundamentals of property management, installation engineering, architectural engineering, and construction engineering, are in urgent need of clarification by the research community.

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Curriculum Vitae

Michiel Paul Horikx was born in 1956, in The Hague, the Netherlands. He attended the Lyceum Augustinianum in Eindhoven and completed his secondary education in 1976. Subsequently, he first studied architectural, and later structural engineering at the Eindhoven University of Technology. He completed his master's thesis in 1983.

After completing his military service he worked with the Hollansche Beton Groep, at that time the largest civil engineering contractor in the Netherlands. As a structural designer, he was involved in large scale projects, including offshore and bridge design. From 1988 up to 1992 he held the position of conceptual designer and engineering manager of the steel structures – retaining wall, trusses, and ball joint – of the Maeslant Storm Surge Barrier.

Since 1992 he has worked as a senior lecturer and manager at the Amsterdam University of Applied Sciences and has been responsible for the design, implementation and management of the following higher education programmes: Bachelor's in Civil Engineering, Bachelor's in Structural Engineering, and Master's in Structural Engineering.

In 2019 he has been appointed as professor of the national Lectorate Structural Safety, commissioned by the national concrete association BV, the national steel association BmS, and the Amsterdam University of Applied Sciences, including their corresponding professional master's programmes in structural design.

In response to present-day societal and technological developments, the national concrete association BV, the national steel association BmS, and the Amsterdam University of Applied Science – including their corresponding professional master's programmes in structural design – established a national lectorate "Structural safety" starting 1 September 2019 with a duration of 4 years. With regard to structural safety the lectorate's primary objective is to contribute with innovative higher education development, including textbook materials, and practice-based research on sustainable structural materials and sustainable structural systems.

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