Synergy between structural and architectural engineering: the point of view of the structural engineer

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Abstract

Two departments of Vrije Universiteit Brussels (VUB), being the Department of Architectural Engineering (ARCH) and the Department of Mechanics of Materials and Constructions (MeMC), both in the Faculty of Engineering, are both scientifically active in various aspects of structural and architectural engineering. What, at first sight, could be seen as reciprocal attempts to cover each other's fields of research activities is far from the truth. On the contrary, their continuous collaboration, which originated years ago, showed an intense synergy, not only in the field of scientific research, but also in teaching and external activities. The present paper illustrates that statement with case studies, taken in the three activity components, from the point of view of the structural engineer and shows that "one and one can be (significantly) more than two".

A parallel paper will report on the point of view of the architectural engineer at VUB.
Keywords: civil and structural engineering, architectural engineering, collaborative research, teaching, extension and outreach activities.

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1 Introduction

There already exists a long tradition of collaboration between the Departments of Civil and Architectural Engineering at VUB, the latter being founded in 1979, some ten years later than the former.

Both Departments have continuously reported their scientific progress in Conferences and Journals, in which WIT Press Publications take a significant place. Suffices to consult the series on “WIT Transactions on The Built Environment” [1] and to mention the papers presented at and published in the proceedings of Conferences like HPSM, OPTI, STREMAH, ECOSUD and now MARAS.

Both departments were lately confronted with the problem of retiring senior staff. In MeMC, this affected three heads of research groups, all three of them full professors: Jan Wastiels was heading a research group on brittle materials, Hugo Sol on inverse methods and composite materials and Willy Patrick De Wilde on structural engineering. The latter also temporarily headed ARCH in 2006, which gave him more insight in the possibilities of an intense collaboration between the two departments at all levels: research, teaching and extension.

It was then also clear that a significant investment had to be done in the activities covered by MeMC. Thanks to the support of the Faculty of Engineering, but in the first place to the cohesion of the MeMC group, the succession of in particular W.P. De Wilde was already prepared in 2006. This led to the possibility of continuing almost all research, teaching and extension activities in the field of structural engineering. Three junior staff members were appointed and joined Danny Van Hemelrijck, now HOD, responsible for all experimental activities of the department:

- Dr. Lincy Pyl, civil engineer, with expertise in both theoretical-numerical and experimental aspects of steel constructions, in particular in thin walled steel structures;
- Dr. Tine Tysmans, civil engineer, with expertise in concrete and brittle materials, with a focus on lightweight structures applications;
- Dr. Dimitrios Aggelis, mechanical engineer, bringing in his expertise in continuum mechanics and experimental techniques, applied to composite materials.

It is undoubtedly the merit of these three new staff members, not only to have continued, but also significantly expanded the activities of MeMC in the mentioned fields. But, most of all, they have understood how a parallel development, occurring within Architectural Engineering could be of mutual benefit. In particular the activities in structural steel engineering were taken over by the first author L. Pyl, and unfolded new possibilities of collaboration with the group of Niels De Temmerman, Marijke Mollaert, Lars De Laet and co-workers from ARCH, more particularly, but not exclusively, in the field of “Transformable structures”.

2 Scientific research in structural engineering

It is important to mention that, since approx. 2000, the scientific collaboration of MeMC with ARCH was always very intense:

- Research groups from ARCH will report in a parallel paper and comment upon the synergy which they achieved with MeMC. There are essentially three research fields, which generated academic activities (research, teaching and extension):
  - Marijke Mollaert, structural engineer with VUB affiliation, was at the cradle of and headed a European group on "lightweight textile structures", Tensinet. She also specialized in Architecture, hereby collaborating with P. Samyn. She was the PhD thesis director of, among others but relevant in this context: Niels De Temmerman, Lars De Laet, Caroline Henrotay.
  - Ine Wouters, architectural engineer, concentrates her research efforts on and leads a research group on restoration of architectural heritage and re-use strategies. Her contributions to the STREMAH Conferences of WIT give a good idea of their collaboration with structural and materials engineers. Most of her PhD students have left after graduation, but today occupy important positions as civil servants and decision makers.
  - Hendrik Hendrickx, architect, co-headed the research group "4D Design" which he founded with W.P. De Wilde, after having met at a STREMAH conference in Bologna (2002).

From MeMC's side:

- A research group on so-called "*Morphological indicators*" started its activities in 2000 and brought together staff and students from both MeMC and ARCH, as well as a few other schools. Only mentioning the senior researchers and doctoral students, as well as their contribution to this field of structural analysis and design research:
  - MeMC: W.P. De Wilde, J. Van Steirteghem, B. Verbeeck, T. Vandenbergh, L. Pyl;
  - ARCH: P. Samyn, structural engineer, CEO of Samyn and Partners, Architects and Engineers, Brussels, Belgium, who also was part time professor in ARCH;
  - External contributors/collaborators: P. Latteur, now professor in Université Catholique de Louvain, Belgium; C.W.M. Sitters, associate professor in Moi University, Eldoret, Kenya; also senior collaborators of P. Samyn, among which T. Vilquin.
- A research group on "*4D design of structures*" originated in 2002 (see above): Only mentioning the senior researchers and doctoral students, as well as their contribution to this field of structural design research:
  - MeMC: W.P. De Wilde, W. Debacker, A. Paduart, L. Pyl;
  - ARCH: M. Mollaert, H. Hendrickx, C. Henrotay;
  - External contributors/collaborators: C.W.M. Sitters, associate professor in Moi University, Eldoret, Kenya.

3 Research fields in strong synergy with ARCH

3.1 Conceptual design of structures: the use of morphological indicators

The main objective of the research group was to bring together structural and architectural research engineers and develop tools, which would allow architectural engineers to come up with feasible preliminary designs. One calls these designs *feasible*, in the sense that they satisfy the three basic requirements of the structural Eurocodes (EC): *strength, stiffness and stability* requirements should be met. Moreover, these tools should allow to compare various structural typologies and topologies, and produce designs, close to minimum volume structures.

These conceptual designs can then be detailed by the structural engineers, in order to meet additional requirements: an *acceptable dynamic behaviour* for lightweight/long span structures and *sustainability* through responsible material, structural components and connections choice.

It has been the significant contribution of P. Samyn, then part time professor in ARCH, to show that "*morphological indicators*" (MI), which are dimensionless numbers and measuring a "*performance*" (strength and stiffness in the first place in Samyn's thesis [2, 3] and stability in Latteur's thesis [4] of a structure, can considerably reduce the complexity of the preliminary design problem. The design guides that Samyn and his collaborators, mainly from his own office and from MeMC and ARCH, developed have proven to contribute significantly to better preliminary designs.

3.1.1 Design for strength

It is the ambition of Samyn [3] to use a minimum of parameters to describe the morphology of a structure. He hereby supposes a homogeneous structure made of an elastic material with elasticity modulus E and limit stress σ. The structure can be framed within a minimal rectangular window with dimensions L and H. The aspect ratio of this window L/H is called slenderness and one can represent the resultant of the loads by F.

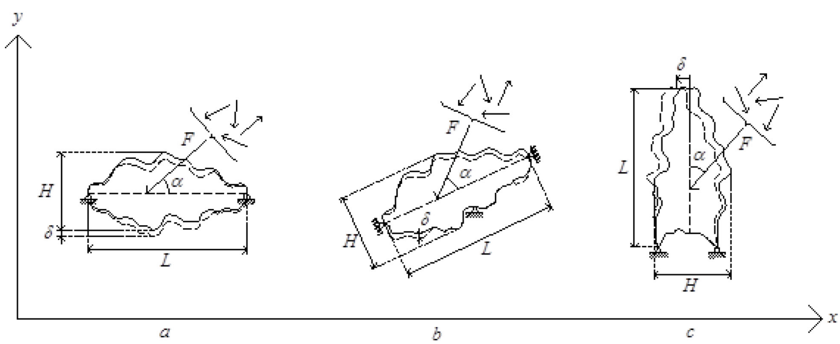

Figure 1: Slenderness of a structure under loads with resultant *F*.

A way to achieve a minimum volume structure, for a given programme of loads (like e.g. prescribed by EC1) is to re-size all elements into a *fully stressed design* (fsd). Additionally, for statically determinate structures, for which internal efforts in all the elements are independent from the section properties of the other elements, it is straightforward to find an fsd with a simple proportionality rule. Starting from this idea, Samyn [2] proposed a first morphological indicator, which he called "*volume indicator*", defined by $W = \sigma V/FL$, in which V is the volume of (fully stressed) material. He shows that $W = f(\frac{L}{H})$, and takes the form $W = C_1\left(\frac{H}{L}\right) + C_2\left(\frac{L}{H}\right)$, C_1 and C_2 being constants, depending on the structural typology and topology (bars configuration). For a wide category of trusses, the values of the two constants are established, either analytically, or through interpolation of calculated point values. This allows to us establish graphs for different typologies and configurations of trusses. As an example we show the graph giving W (L/H), for the family of Warren trusses and in function of the number n of panels.

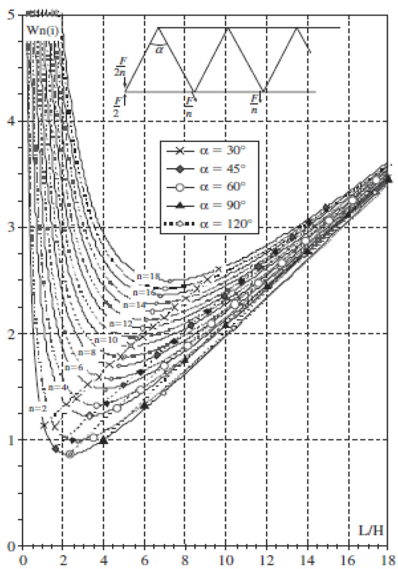

Figure 2: Volume indicator W for a family of Warren trusses only considering resistance.

The volume indicator W is thus, according to P. Samyn, the hierarchically most important indicator, allowing for a minimum volume preliminary design of structures. In the methodology prescribed by the Eurocodes it allows for the correct sizing of elements in ULS (Ultimate Limit State).

3.1.2 Design for stiffness

The stiffness requirements of the Eurocodes require that, in SLS (Serviceability Limit State), the deflections of the structure be limited to a fraction of the span.

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Therefore, P. Samyn [2] proposed a second MI, which he called "Displacement indicator": $\Delta = \frac{E\delta}{\sigma L}$. In order to establish similar graphs giving Δ in function of the slenderness L/H, for various topologies and typologies, the values of d, being the maximum displacement in the loaded structure, had to be established. As this involves the use of (Mohr's) integrals, the development of the theory was linked with the calculability of the integrals, from analytical to numerical, via symbolic calculus. Important to mention is that the displacement indicator is proportional to δ/L, which is exactly the value one wants to limit in the SLS calculations.

3.1.3 Design for stability

Several aspects of structural instability have been investigated and reported by the research group. In his PhD thesis [4], related to buckling phenomena, P. Latteur introduced a morphological indicator Ψ, which he called "buckling indicator". This factor $\Psi = \frac{\mu\sigma L}{\sqrt{qEF}}$ gives an indication for the impact of the buckling tendency of the compression elements on the total volume, in a structure with span L, composed of bars with a form factor $q = \frac{I}{\Omega^2}$, where I is the minimal second moment of inertia and Ω the section area in a material with Young's modulus E, with at least one section dimensioned on its allowable stress σ , subjected to a system of loads with total resultant F. μ is the proportion of the buckling length of the compression bars over their geometrical length (which depends on the connection type, e.g. for pinned trusses, NBN ENV1993-1 (2002) allows μ = 0.9). The consideration of buckling modifies the element sizing, increasing the precision of the optimisation process at the cost of one extra parameter (Ψ). It enables the evaluation of the extra necessary volume of material to avoid buckling. Moreover, the definition of the indicator of buckling clearly demonstrates that the buckling sensitivity depends on the span-load ratio ($L/\sqrt{F}$). This quantity is defined as the structural index by Shanley [7] and shows that morphological indicators, although they are dimensionless, in fact depend on (non linear) scale effects.

Latteur [4] also tackled a second important problem by including the self-weight through the indicator of self-weight $\Phi = \frac{\varrho L}{\sigma}$, ρ being the material's specific weight. Its value gives an indication for the fraction of the allowable stress necessary to carry the structure's self-weight. As it is clear that the self-weight depends on the total span of the structure, the scale of the problem is also included by considering self-weight. Also worth mentioning is that the consideration of self-weight enables a more precise estimation of the necessary volume of material for strength purposes, but that it does not change the hierarchy among the different structural topologies. The values are just rescaled, and "the lightest solution remains the lightest".

The work of Latteur, further developed in the research group on structural morphology, clearly indicated that the influence of buckling on the volume of material can be significant, even when the best available solution is used.

In order to further lower the volume of the compressed elements, Van Steirteghem [5], an architectural engineer pursuing doctoral studies in MeMC, proposed a significant reduction of the buckling length of compression members, by introducing stay cables and cross arms for their stabilization. Considering different cross arm geometries and connections, pretension, buckling modes and imperfections, he developed a design procedure leading to an optimal or lightest compression element.

3.2 Additional design criteria

The resulting conceptual design must yield a structure showing a sound behaviour in both the serviceability limit state (SLS) and in the ultimate limit state (ULS), also meaning that the three essential criteria should be satisfied: strength, stiffness and stability.

However, the question very often remains open as to which of the three criteria is overruling the other ones. De Wilde, in [6], tries to show that a conceptual design methodology can be developed, hereby using the concept of morphological indicators together with a *structural index* (introduced by Shanley [7]).

3.2.1 Design for mechanical comfort

In the development of morphological indicators, dynamic effects were almost not considered during preliminary design. However, an optimum obtained by minimising the volume, hereby only considering strength, often results in solutions with problematic dynamic behaviour. The research group was aware of this pitfall and, of course, knew about the problems which had affected the Millennium Bridge, at its inauguration in London.

To avoid these problems the stiffness, mass and/or damping characteristics must be modified, implying a volume increase, additional (damping) equipment and as a consequence a cost rise.

It would thus be interesting to introduce optimisation tools (of MI type?) that considers/predicts dynamic behaviour at the stage of conceptual design, and such that an optimum can be obtained without the necessity to alter the (strength-optimised) construction drastically afterwards. A study by Vandenbergh and De Wilde [8] presented a basic analysis methodology, hereby giving an answer whether vibration norms/guidelines ask for a modification of the design or not, at conceptual design stage. Worthwhile to mention is that this methodology also gives an answer to the question that very often arises when designing lightweight and/or long span structures: “design for strength” or “design for stiffness”? This problem was addressed by Vandenbergh *et al.* in [9]. Analysis of the indicator of displacement Δ, the indicator of first eigenfrequency Θ and the indicator of global planar stability Λ_{cr}, proves that even at the stage of conceptual design, one can determine whether “design for stiffness” or “design for strength” is the designer’s priority and thus must be addressed in the first place. Vandenbergh consequently proposes the following procedure:

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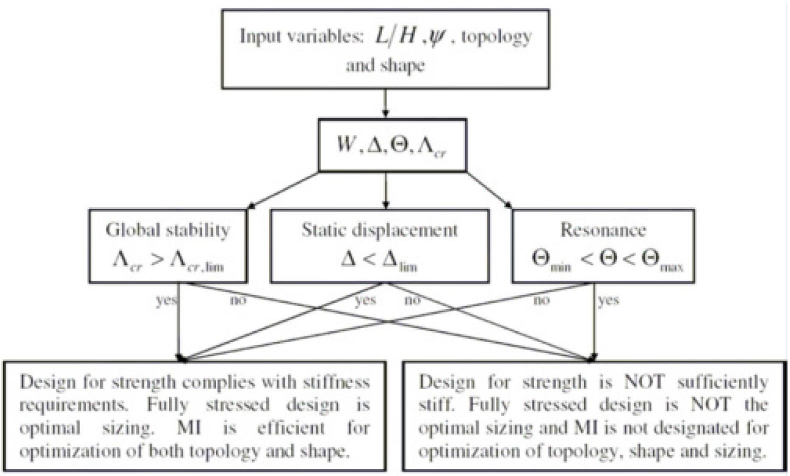

Figure 3: Flowchart for the appropriate use of morphological indicators at conceptual design stage.

Hereby, other empirical observations are important:

- When one foresees risks for instability phenomena, it is better to approach the problem through “design for stiffness”.
- When designing lightweight structures it is almost always the design constraints in the SLS that prevail over those for the ULS. In other words, these constructions have an important reserve in strength, and they thus show a much higher value of W than the optimal one!
- The penalty imposed by additional material consumption, in order to avoid unacceptable vibrations, is much more severe than the one controlling (in)stability.

3.2.2 Design for sustainability

Sustainable design: It is undoubtedly in the field of “*sustainable design*” that the collaboration between MeMC and ARCH has been the most intertwined. The creation of a mixed research group on “4D-Design of structures” was at the basis of three important doctoral theses, which have received wide acclamation, not in the least for Paduart’s [10], which was awarded the prestigious Gustave Magnel prize 2012. Also the scientific work of Henrotay *et al.* [11] and Debacker *et al.* [12], under the guidance of M. Mollaert, H. Hendricks and A. De Herde (from UCL, Louvain-la-Neuve, Belgium, specialist in energy problems) and De Wilde, has been reported in various editions of the Transactions on the Built Environment [1]. It is important to mention hereby that simulation tools were introduced, as they were needed for objective assessment of competing solutions: life cycle cost (LCC) and life cycle analysis (LCA).

Material use in structural engineering: The quest for lesser material consumption in advanced steel design brings one to thin walled profiles, hereby achieving stiffness requirements through the form of the sections, open or closed.

Their possibilities are, for obvious economic reasons, heavily investigated by working groups of EC3, to which the Belgian researchers have always offered significant contributions, amongst others (Pyl *et al.* [13–16]). The Laboratory of Steel Constructions in the University of Liège, founded by Charles Massonnet, are worldwide known especially in the field of joints, and the actual group, headed by J.P. Jaspart, is regularly strengthened by its collaboration with L. Pyl, who contributed to their scientific activities. Important spin-off activities are to be mentioned in the teaching and Master's theses' activities at Moi University, Eldoret, Kenya (see further).

Roof design with modular sandwich elements made of fiber reinforced cementitious lightweight elements was studied by De Bolster in her doctoral thesis [21]. A remarkable finding was that a "design for stiffness" approach was to be considered, the repeated wind loading and resulting fatigue of the brittle material (in SLS!) being more damageable, than the storm in ULS.

Brussels Retrofit XL is a multidisciplinary platform that brings together Brussels research teams with different expertise in the context of retrofitting aspects relevant to the Brussels housing market. In the project LightComp, T. Tysmans heads a group of researchers working on the design of Lightweight building Components for the renovation and reconversion of existing buildings. In the project DynStra, N. De Temmerman and A. Paduart develop Dynamic Reuse Strategies for the retrofitting of post-war housing in Brussels. I. Wouters is the project leader of the project RetroCo in understanding and conserving the post-war housing stock in Brussels (1945–1975).

4 Synergy in teaching

In the field of "structural design and analysis", the teaching activities are clearly separated: the students in architectural engineering are instructed in conceptual design of high rise and large span structures (lightweight footbridges are an attractive subject), whereas the structural engineers concentrate on analysis of structures based on the design rules of the Eurocodes and detailing of the structure.

This also happens at the level of the student projects, initiated by the architectural engineers and completed by their colleagues from structural engineering. Common briefing sessions are organised on a regular basis and allow for constructive criticism.

5 Services for thirds: 3 case studies

5.1 Restoration of the spire of Brussels Town Hall (approx. 1994)

A paper by Dumortier and Wilde [17] presented a finite element analysis of the Tower of Brussels City Hall, which was contracted to MeMC by Arch. Eng. C. Nijs, then also a colleague lecturer of ARCH and on behalf of the City Council of Brussels.

Both linear and non-linear analyses were necessary, due to the low tensile strength of the original construction material and the need to simulate stress redistribution. The mass and wind loading (normal or exceptional) were to be taken into account. Different reconstruction sequences had to be investigated.

The main objectives of the study were:

- to determine the most vulnerable regions in order to properly plan the reinforcement and the restoration of the tower;
- to examine the influence of metallic reinforcements in the cap, which had been placed during previous restorations;
- to determine the force distribution in the structure, in order to make appropriate predictions of the influence of the removal of parts during restoration and to predict deflections under given loads to allow continuous structural monitoring during the works.

The finite element method gave a thorough understanding of the structural behaviour of this complex structure, through a model with approx. 300,000 DOF. This study showed that the third gallery and the spire were not as well designed and constructed as the original parts (two lower galleries) were. It also showed the effect of reinforcements in the cap to be minimal.

5.2 Restoration of the Brussels Court of Justice (approx. 1997)

This is a typical example of a mixed collaboration between MeMC and ARCH, in which the technical aspects had to comply with the historical importance of the building. The co-authors were doctoral students of the two departments. The court of Justice is a famous monument, designed by J. Poelaert around the turn of this century. During the occupation of Belgium in World War II, one of the domes was severely damaged by fire. Moreover, the totality of the structure has undergone severe "ageing" phenomena, so that the decision to restore the building (and the way to do it) was subject to the analysis of the actual state of the structure. For this purpose about 2700 reference points of the structure were measured by surveyors.

The paper by Declerck *et al.* [18] the first author being architectural, the three other structural engineers, develops the historical context of the structure, and the followed methodology in the decision process related to the restoration of the building.

Especially the aspects related to the security with respect to the stability of the structure are discussed. Both 2D- and 3D-models were developed, in order to investigate the residual strength, the stiffness and the stability problems in the most deformed arch. The finite element models showed us that the original concept of Poelaert's domes was well designed. Even compared to the contemporary European standards, taking into account the damage due to the devastating fire, the structure is still sufficiently stable if the service loads are limited. An additional semi-public function, e.g. for exhibition purposes, required substantial reinforcements and so this idea was abandoned.

5.3 Setting up an MSc programme in Structural Engineering in Kenya

In 2007, VLIR_UOS, the universities development cooperation agency of Flandres, decided to launch an ambitious academic programme with *Moi University, Eldoret, Kenya* as partner. Among the 6 funded projects, involving the strengthening of the departments in agriculture, medicine, computer sciences, gender studies, the major part of the budget was spent on the Department of civil and structural engineering (DSCE) for setting up a MScEng in Structural Engineering and a MScEng in Water Engineering, in collaboration with and under the responsibility of MeMC. It was also foreseen to assess the program in 2012, which resulted in the funding of a second phase, covering the period of 2012–2017, and now concentrating on research at both MScEng and PhD level. In the field of structural engineering, it was decided to put the emphasis on steel constructions, related to telecommunications and movable modular and transformable bridges. For both research and teaching at Master's level, the Departments ARCH and MeMC once again collaborated successfully, which resulted in various scientific papers, Master's theses and shortly a first PhD thesis in Structural Engineering. For the period 2012–2017, the research efforts are related to "Structural Morphology" and "4D design" of steel structures, and headed by Lincy Pyl. A common publication has already been presented by Pyl and Sitters [19], at HPSM VI, in 2012, in which the aspects related to sustainability are put forward. As far as Structural Morphology is concerned, applications have been presented by Pyl *et al.* [20].

6 Conclusions

Through collaborative research between architectural and structural engineers, a synergetic effect has been achieved, which allowed for each group, MeMC and ARCH to generate a significantly larger scientific, pedagogical and societal output than acting separately. The main reason is to be found in the complementary aspects of their respective trainings, but also in the introduction of the necessary engineering components into the architectural engineer's programme.

Also to be mentioned are the shifts of attention from mere "structural engineering" ("design and build") to "sustainable design" (design, build, operate, maintain, repair, end-of-life handling), which require additional research tools.

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