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On Conceptual Design, Assessment of Existing Structures, Research and Standards

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Abstract

The author has had the good fortune to be active for the past four decades almost uninterruptedly as a designer, researcher, teacher, and standards-writer. Over this time, he has been observing a tendency for an increased degradation of the profession, with the segregation between education, research, and practice. It is the opinion of the author that each of these fields has been experiencing individual advances isolated from a holistic view of the profession, compromising the evolution and, consequently, the impact of civil engineers in society. Consequently, the profession is becoming less and less attractive for bright and motivated young people. It is the opinion of the author that such trend can only be inverted by placing more emphasis on the creative and intellectual components in each of the fields of education, research, and practice, as well as by bridging the gaps between them. These considerations are supported by personal experience which is shared in this article by presenting some instances of conceptual designs.

Keywords: *Conceptual design, dimensioning, assessment, research, standards.*

Introduction

Several great structural engineers of the last century have already emphasised the importance of structural design in the work of engineers (Maillart [1], Nervi [2], Freyssinet [3], Torroja [4], Schlaich [5]). Although the profession of civil engineering shares the same roots as those of architecture (until the 18th century, they were simply referred to as builders), the separation became necessary with the industrial revolution. At that moment, construction using relatively expensive materials (cast iron and steel, and later reinforced concrete) made necessary to calculate and dimension them, which required new skills and specific education. However, for at least a century now, the scientific side of structural engineering (analysis, verification, dimensioning) has taken over [6] and nowadays, our masters' warning is even more justified. If we compare ourselves with our architect colleagues, with whom we still share the design and project activity, the evolution of the last few decades has been rather unfavourable. The trend in students' number in both disciplines bears witness to this (Figure 1). Although the trends were similar until recently, and essentially correlated with the economic situation in the construction industry, for some time now we have been witnessing a reverse trend (see Figure 1).

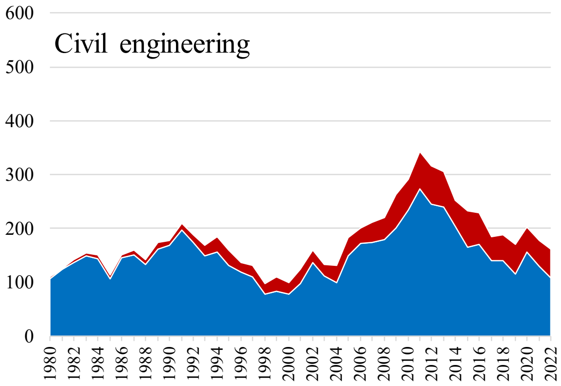


Figure 1. Number of students in civil engineering and architecture starting their curricula at both technical universities in Switzerland (male in blue; female in red, data by the Swiss Federal Office of Statistics).

We should be concerned by the fact that our profession is seen by young people, perhaps wrongly, as being too technocratic, having little to do with solving society's challenges, and attracts therefore fewer and fewer young people. It is also worth mentioning that, unlike architecture, where in some universities, more than half the students are female (Figure 1), our profession is having difficulty attracting young women.

The challenges of climate changes and artificial intelligence, with all their risks and opportunities, make it more urgent to reflect on the current situation and possible outcomes. The thesis developed in this text is that engineers should once again be able to free up more time for design and project-related activities, and with more creativity in all activities.

About design, conceptual design, and creativity

First of all, what is the most noble and interesting activity of the engineer, and what should be the added value of the engineer's activity to the society?

According to Wikipedia, "*engineers, as practitioners of engineering, are professionals who invent, design, analyse, build and test machines, complex systems, structures, gadgets and materials to fulfil functional objectives and requirements while considering the limitations imposed by practicality, regulation, safety and cost*" [7]. Interestingly, in this definition, the creative component of engineer's work is listed at the beginning of the engineer's activity. With this respect, the etymology is also interesting: the word *engineer* (Latin ingeniator) is derived from the Latin words "*ingeniare"* (to invent, to plan, to devise) and "*ingenium"* (cleverness, therefore, "*engineer*" has the same etymology as "*genius*").

Design is a word that has among civil engineers, especially in English, a too broad meaning that often lends itself to confusion. To avoid misperceptions, the word *'design'* should be reserved for the creative and intellectually noble part of the engineer's activity, while another definition should be reserved for the technical part, associated with dimensioning and verification. Current standards for structural engineering have also contributed to the misperception surrounding the word *design*. In fact, *design values* used in our standards [8,9] have very little to do with design, being rather values needed to dimension a new structure or assess an existing one (the definitions "valor de cálculo" in Spanish, "Bemessungswert" in German, "valeur de calcul" in French and "valore di calcolo" in Italian correspond better to the concept than the English term "design value").

To overcome this misperception related to the word design (here again, this is mainly a problem of the English language: in German, Italian, and French, we respectively differentiate Gestaltung / Bemessung; progetto / dimensionamento; projet /dimensionnement and certainly other languages also make this distinction), the definition of *conceptual design* was introduced at the end of last century when a congress called "Conceptual Design of Structures" was organised by Jörg Schlaich at Stuttgart for the International Association for Shell and Spatial Structures in 1996 [10].

With this respect, the International Federation for Structural Concrete (*fib*) took the initiative, based on a precursor idea by Hugo Corres, to organise a series of symposia on Conceptual Design every two years. The first event took place in Madrid in 2019 followed by the symposia in Attisholz (Switzerland) in 2021 and in Oslo in 2023, to be pursued by events in Rio de Janeiro in 2025 and in Italy in 2027.

When we initiated the 2021 symposium with my colleague Joseph Schwartz, we discussed much about what conceptual design is (and what is not). During the symposium, it became evident that the variety of definitions of conceptual design was no less than the number of participants at the conference. However, we believe that conceptual design should be defined to avoid the risk that at the end, everything is considered belonging to it (in fact, to avoid again the confusion related to the term "design"). For this reason, we have tried to formulate a definition in our contribution to the book "Conceptual Design of Structures" [11]:

> "*The term Conceptual Design of Structures denotes the intellectual activity of developing a highly appropriate structural solution - in terms of structural system, shape, materialization, construction method, detailing, etc. – for a given purpose in a defined context. When related to buildings, it follows the programmatic idea of a reconciliation between the discipline of engineering and architecture through the reciprocal integration of load-bearing structure and architectural design concept, with a unified understanding of the interplay of form and load-bearing capacity. This activity is nurtured by knowledge of the functioning of structures and of construction history - although it should never be limited to uncritically applying already known solutions*".

The experience and the success of the first three Conceptual Design Symposia organized by *fib* have shown the need to increase the importance of creativity in the contemporary work of structural engineers. Current and future challenges related to sustainability aspects, to a better distribution of resources in the world, to the correct use of artificial intelligence (increasing the beneficial results and minimising the threats), to the lack of attractiveness of our profession among the younger generations, to the decreasing motivation and increasing frustration of some designers confirm these needs and make a rethinking of our priorities even more important. The structural project and the creativity required to improve it should be at the heart of our commitment. Creativity is also a key aspect to make structural engineering more interesting, to ensure the engineer's contribution as a significant added value, to keep current colleagues motivated in our field and to attract more talented young people to our profession.

All the phases starting from the initial conceptual design to the final execution in the construction site of a structure for a building or for an engineering work such as a bridge require a broad range of skills, the collaboration of many actors within an engineering office, as well as collaboration and interaction with many external actors. Personal experience shows that the creative part is often the most rewarding and has often the most impact on the final quality of a structure, even though it requires relatively little time commitment (Figure 2). In the examples shown in Figure 3, the initial phase of structural conceptual design, starting with the study of the context, the analysis of needs, the proposal of a few sketches up to a pre-dimensioning (typically a very simple manual calculation), took relatively little time, but was then followed by other phases in which everyone's commitment and perseverance were equally decisive in achieving the final quality of a structure. With this respect, detailing plays also a major role and without a professional coordination with other actors (owners, architects, contractors, other specialists, ...) and an efficient transmission of knowledge between them, it would be impossible, nowadays, to successfully finalise a project. In addition, efficient coordination and transmission of information are instrumental to limit the risks of human errors and to control the costs and the final quality of the work. It is therefore fair to acknowledge everyone's contribution, but neither should one fall into the temptation of wanting to quantify contributions only in terms of time and effort. Unlike architectural projects, which have many similarities with our own projects, and where the author of the project is clearly defined, in engineering projects there is often a tendency to keep the role of the *author of the conceptual design* quiet. This is clearly counterproductive. Without falling into the opposite excess, which is common in other fields, where only the author of the project is often mentioned, in our structural projects, this role should be emphasised more so as to motivate young colleagues to be more involved in *conceptual design of structures*. We should therefore speak more often of *'design author'* for engineering works, *'author of structural design*' for buildings in which there is a real creative contribution on the part of the engineer, or simply of '*structural designer*'.

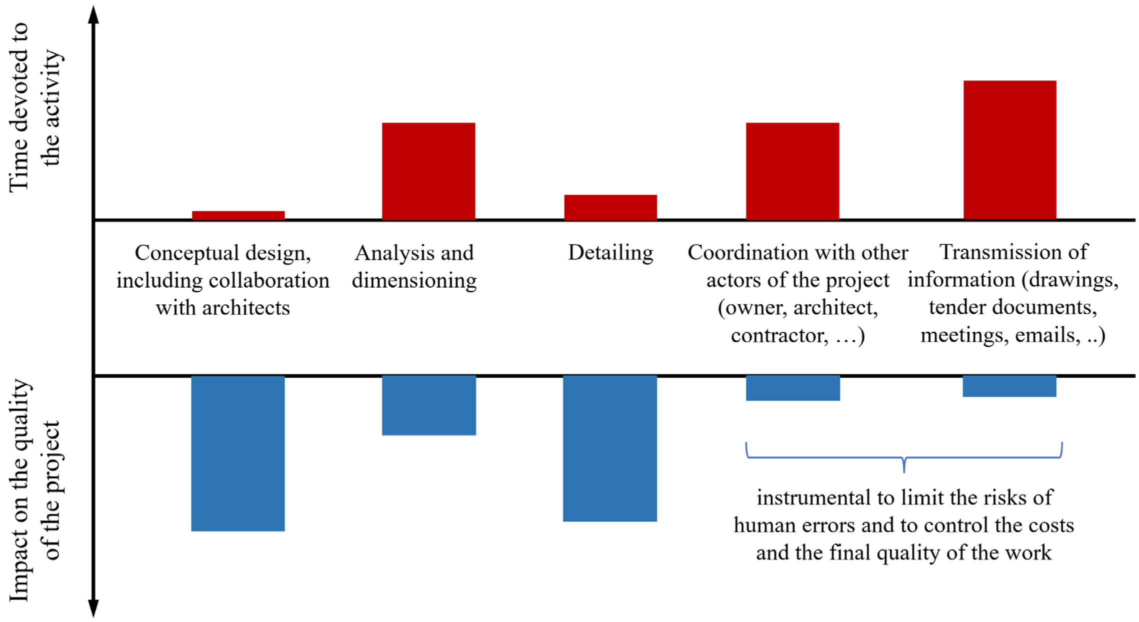
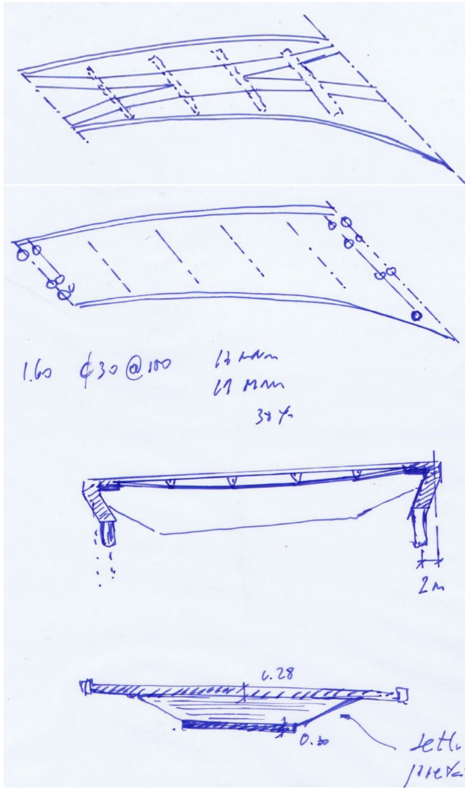


Figure 2. Significance of conceptual design in terms of time devoted and impact on the quality of the structure compared to other engineer's activities.

Still with respect to Figure 2, according to the experience of the author, the situation has deteriorated in the last decades. The introduction of new technologies, accelerating phases such as analysis and the preparation of drawings, instead of liberating more time for the creative component of the profession, has been used to coordination and administrative tasks. This trend must absolutely be inverted since these technological advances will continue (see for instance artificial intelligence). The risk is that the weight of the creative component of our profession will further decrease with time.

Civil engineers should take action and use the new technologies in their favour, for instance using the automation for repetitive and administrative tasks and improving the quality of the projects by dedicating more time to the intellectually challenging tasks instead of searching to reduce the time devoted to the project.



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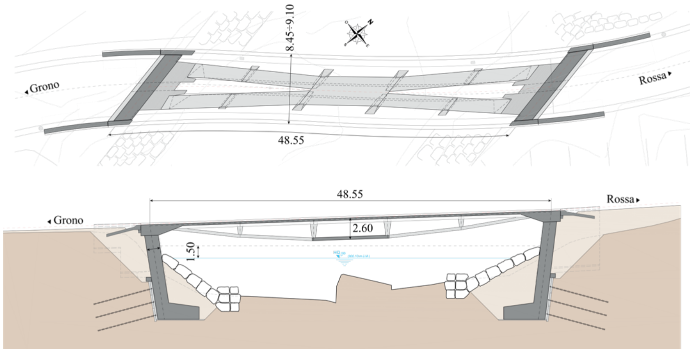


b)

c)

Figure 3. Bridges Auriglia and Loveira over the Calancasca river, Southern Switzerland, (a) sketches for the conceptual design of the Loveira bridge, (b) final design of the Auriglia bridge and (c) photo of the Auriglia bridge (Lurati Muttoni Partner civil engineers, A. Muttoni structural designer) [12].

In the design of structures, a clear definition of the required function and a knowledge of possible construction methods and their economic costs, planning and environmental implications are necessary. In addition, an ability to analyse the constraints and particularities of the site with the landscape and the built environment, a deep understanding of how structures work and a good knowledge of construction history are essential. In this context, it is not a question of adopting uncritically well-known solutions, but of taking inspiration from them, adapting, optimising, and developing them to better meet the requirements of the new project. A creative contribution leads to an evolution of the adopted structural solution. In structural design, revolutionary and disruptive solutions are rare, but continuous evolution is possible and desirable. It is often a question of studying with a critical and curious eye, and, of course, of understanding known solutions, so as to be able to improve them. Our own previous projects are often a privileged source of inspiration because the potential for improvement is better known as a result from the lessons learnt during the completion of the work. Never being completely satisfied with what we have designed and realised is an approach that makes it easier to find a better solution for the next projects. Nevertheless, every project is different, in the sense that the sites, challenges and constraints are different.

Sometimes, innovative solutions result from a desire to improve a project for a very specific situation and can then be adapted for very different cases. The road bridge shown in Figure 3, for instance, is the result of a long evolution that began three decades before when the aim was to design for a client with very limited means the most economical and lightest footbridge possible. The initial idea of a very slender bowstring had the advantage of very simple fabrication, but the problem of being too sensitive to variable loads. To solve such issue, V-shaped tubular connecting elements were introduced between the top chord and the tie-rod made of reinforcing bars. The result was a structure that was halfway between an under-spanned structure and a Vierendeel beam (Figure 4a, [13]). It is interesting to note that Mamoru Kawaguchi arrived at a similar solution a few years later for his Inachus bridge at Beppu, Japan, but following a completely different path (in that case, it was the removal of some diagonals in a lenticular truss that led to the same structural solution [14]). The great efficiency of the first footbridge built in 1987, designed when I was still a PhD student, then persuaded me that bridges and other structures could be built adopting the same structural solution. A few years later, the opportunity arose to apply the same idea to the construction of a road bridge (figure 4b). The short length of the structure (only 50 m) meant that an integral solution, with neither expansion joints nor mechanical bearings, was suitable. The deck was therefore clamped in two piers to form a frame. The choice of material, prestressed concrete for both the deck and the bottom chord, meant that the V-shaped tubular elements of the footbridge were replaced by trapezoidal reinforced concrete walls. A visually different solution, but identical from a functional point of view (these elements were designed using the strut-and-tie method, as if they were two linear elements). Several projects for road and rail bridges as well as roof structures in steel, reinforced concrete, and mixed structures for a wide variety of situations, were subsequently completed adopting and adapting the same principle (Figure 4, [13,15]).

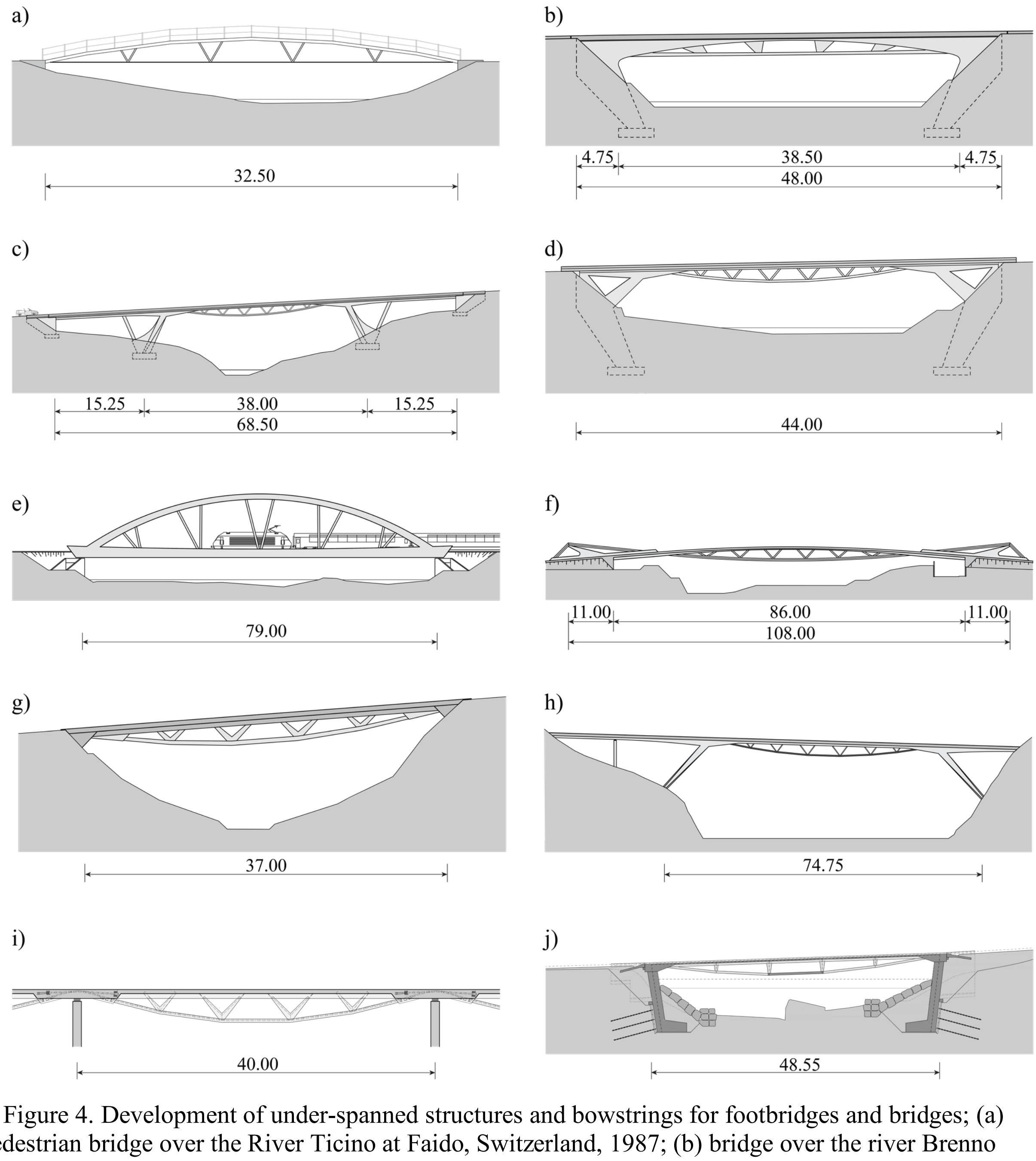


Figure 4. Development of under-spanned structures and bowstrings for footbridges and bridges; (a) pedestrian bridge over the River Ticino at Faido, Switzerland, 1987; (b) bridge over the river Brenno

at Loderio, Switzerland, 1993-94; (c) Bridge at Odogno, Sitzerland, 1995-96; (d) Bridge over the Ticino river at Villa Bedretto, Switzerland, 1996, (e) Design competition or a railway bridge in Switzerland, 1992; (f) Design competition or a reviver in Senigallia, Italy, 1995; (g) Competition for a bridge in Corticiasca, Switzerland, 1997; (h) Project for a Bridge over the Reddalskanalen, Norway, 1996; (i) Study for continuous bridges in Norway, 1997; and (j) Bridge Auriglia over the Calancasca river, Switzerland, 2018-2021 (see also [13,15,12]).

A similar development took place with the idea of inclining toward the span the two piers of the frame shown in figure 4b. In this bridge, this solution had been adopted to facilitate earthworks and the construction of the foundations due to the presence of a road nearby. Positioning the foundations offset from the end of the bridge also had the advantage of reducing the horizontal thrust, thus reducing the risk of horizontal settlement of the foundations, which is particularly problematic for frames with short piers. This principle has been used for other projects (see, for instance, the bridge in Figure 4d).

The project Figure 5 was proposed as a variant to the original project consisting of widening a historic masonry bridge adding a new deck slab in concrete, which would have significantly altered the appearance of the bridge and given rise to considerable costs due to the need of strengthening it. The idea was therefore to create a new structure that was as slender as possible, and with a relatively long span over the river in order to preserve the view of the old bridge and its support on the rock in the middle of the river, but with enough character to avoid appearing banal. The old bridge could then be used for soft mobility. The choice for the new structure was therefore made to clamp the deck in two inclined piers to form a frame, but to place the piers that connect the foundations to the deck mostly in the ground, allowing them to almost disappear. The slenderness of the deck is further enhanced using two support struts. Here again, the idea to incline the piers was adopted in a different situation and was instrumental to achieve the goals of a structure that is as slender as possible and of buried, low-profile abutments, while requiring limited earthworks. The piers-struts-deck system was designed as a monolithic structure in which all the shapes and dimensions were defined based on the internal forces that could be studied using the strut and tie method (see Figure 5) and the stress field approach. Evidently, the great builders such as Maillart, Freyssinet, Nervi, Torroja and others were able to conceive similar structures and forms based on intuition and calculation, but today, we can do so with the most modern means [16].

Because the site did not allow the existing bridge to be placed too far away, the new bridge was also designed to limit the presence of structural elements close to the masonry bridge. The main structure was therefore designed as thin as possible (1.10 metres) and positioned on the axis of the bridge, where the bridge deck slab essentially functions as two cantilevers on either side.

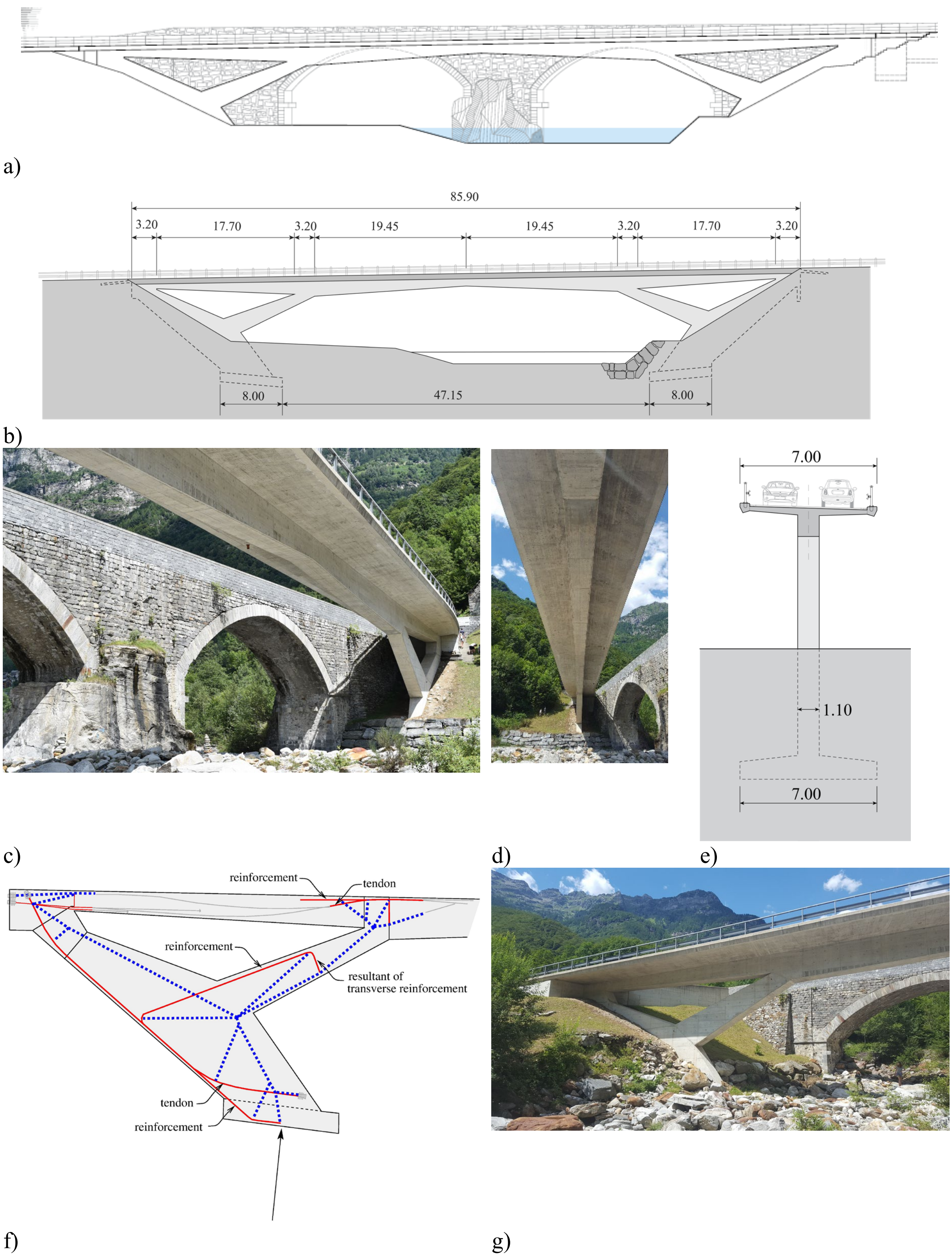
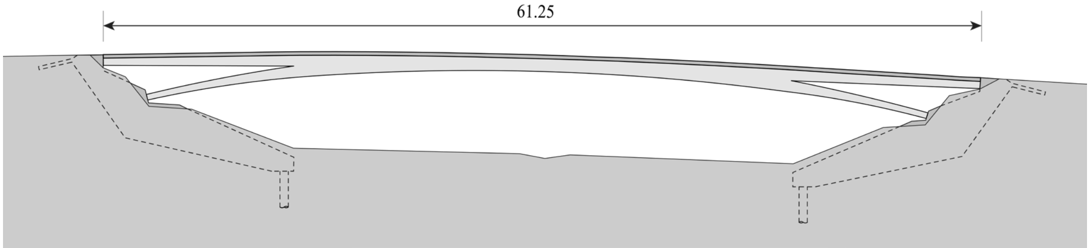


Figure 5. Verzasca Bridge at Frasco, Switzerland; (a) elevation showing the existing masonry bridge; (b) scheme of the system; (c), (d) and (g) photos; (e) cross section; and (f) strut-and-tie model of the abutment (Lurati Muttoni Partner civil engineers, A. Muttoni structural designer, with Michele Arnaboldi architect) [17].

The same design principle could be applied in a more recent project, consisting of a very slender footbridge over the motorway near Lausanne, Switzerland. The initial project, resulting from a design competition, with a ribbon stretched over the motorway, had to be abandoned because of (1) the difficulties of draining of the water from the deck onto the motorway, and (2) the considerable tensile forces of the stress ribbon, which would have had to be anchored in a very poor ground. The idea was therefore to replace the stress ribbon with a very slender arch (Figure 6). Here, the thrust of the structure is carried by abutments in the form of pre-stressed recumbent piers. Once again, the same principle was adopted, where the geometry of the whole system is designed to cancel out the horizontal thrust so that the whole structure can be supported on vertical piles.



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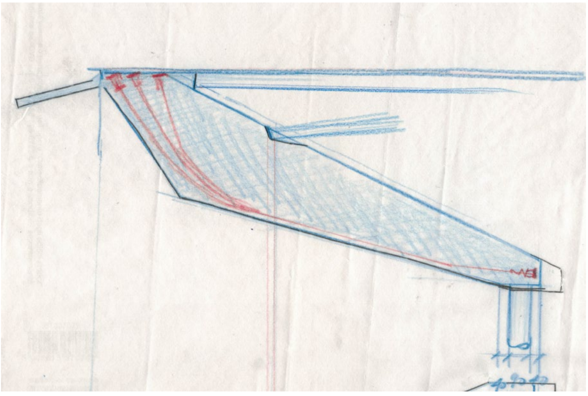

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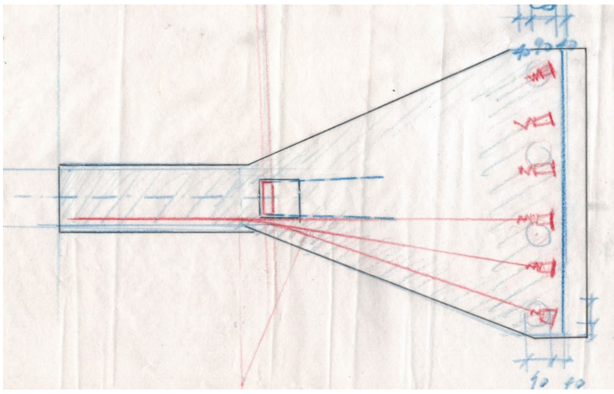

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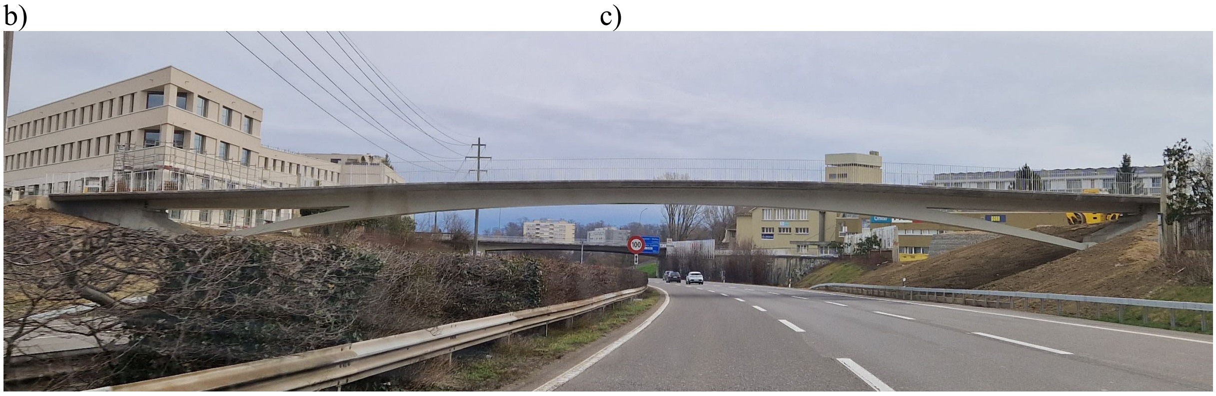


d)

Figure 6. Footbridge “Cèdres” near Lausanne, Switzerland, (a) Scheme of the system, (b-c) conceptual design including study of the prestressed abutments (A. Muttoni structural designer), (d) view of the finished structure (MC2 engineers, Cano Lasso Architects, Muttoni and Fernandez engineers, completed 2024).

The two examples in Figures 5 and 6 show that the same idea can evolve into completely different projects. Solutions can be adapted to the requirements and constraints of different situations, and to the aims of different projects. This is clearly demonstrated in the case of project competitions, where for the same situation and the same requirements, the different participants come up with completely different projects. These projects highlight the importance of structural design, which required relatively little time for these projects, but which strongly influenced them.

Design of interventions on existing structures

In several advanced societies, the centre of gravity of the structural engineer's activity is shifting from the design of new structures to the assessment and intervention on existing ones. This new activity undoubtedly requires specific knowledge and, perhaps also for this reason, a new professional figure specialised in existing structures is emerging. With this respect, it is important to keep in mind that the new knowledge specifically related to assessment and intervention on existing structures should be seen as an addition to, and not a substitute to that required for the design of a new structure. In addition, knowing how to design, how to build and, not less important, how it was designed, dimensioned, and built in the past, is crucial to correctly assess an existing structure (being able to quickly identify hidden defects and to intervene correctly).

The fact that there is less and less construction of new structures in some Countries can be a problem in this respect. Personal experience shows that young engineers who have never had the opportunity to design a bridge tend to have an overly academic and analytical approach. When they begin to assess an existing bridge, they too often neglect a crucial initial phase consisting on a sufficiently holistic qualitative approach, including (i) the identification of inherent weaknesses in the structure, (ii) the considerations on the governing "*assessment situations*" (performed with a qualitative analysis of the critical details perhaps supplemented by some very simplified preliminary quantitative verifications), and (iii) the identification of the main involved uncertainties. Unfortunately, some young engineers tend to immediately focus on the aspects they know best and that they are able to analyse, perhaps neglecting others that are more problematic. In assessments, we all too often see detailed analyses and verifications when the real problems are most likely elsewhere.

It is therefore interesting to note that this shortcoming is analogous to the one previously discussed for the design of new structures, where the creative part of the conceptual design is too often neglected and the analytical part is overdone, resulting in lengthy and not always necessary calculation notes.

When the inspection and assessment of an existing structure reveals problems or weaknesses, the following questions arise: to intervene or not? Preserve or replace? In fact, as shown in Figure 7, the choice is much wider, from doing nothing to demolishing and rebuilding. This choice must always be balanced, trying to avoid any conflict of interest, and above all must always be made based on plausible options and well-defined projects. For instance, in some cases, wanting to preserve an existing structure at all costs, even when the interventions become major, often with considerable risks in terms of the lifespan of the intervention (unfortunately, little is said about failed interventions, which leave a structure that has undergone major intervention still in poor condition after only two or three decades), is neither economic nor sustainable. On the contrary, when a structure of quality can be repaired using simple, effective, long-lasting, and economical interventions, it is also not responsible to replace the structure or to heavily intervene. Once again, the choices are easier if one avoids prejudices and ideological approaches (such as repairing is better than rebuilding because it is more sustainable). If in doubt, it is best to compare two options studied in detail, with a well-balanced comparison of costs, risks, final quality, residual lifespan, environmental aspects, duration of works, impact on users, and so on. The heritage value, in terms of the quality of the structure itself or as a historical witness, shall also be considered in this assessment (the recent guideline by the Swiss Federal Road Administration [18] to account for these aspects in case of bridges and other engineering works is a useful help).

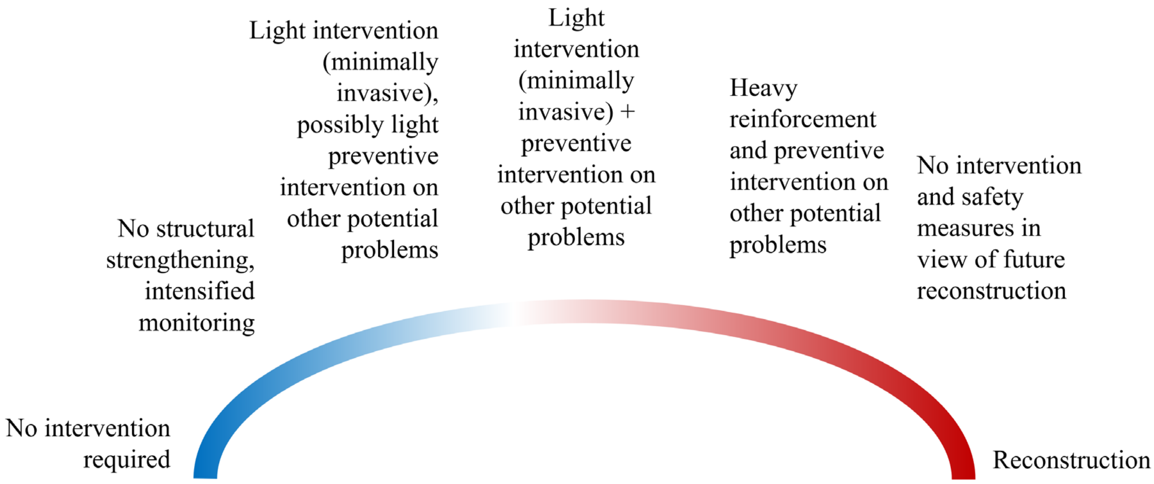


Figure 7. Possible options for interventions on existing structures

When structural strengthening proves to be necessary, the designer may be tempted to affirm the new intervention with a strong and visible gesture, even when a less invasive retrofitting would be possible. Designers should not fall into that temptation. In an analogous and curious exercise, what would people say if orthopaedists would make their work visible? This is not to say that the intervention shall always be hidden, but the designer should always ask himself the question: does the intervention, in addition to restoring the necessary level of safety, really make the structure better? Also, from an architectural point of view? In the case of a positive answer, strong character and visually invasive interventions are possible, but they should always be designed with great care, and must always allow the architectural quality of a fine new structure to be achieved.

In the case of the bridge shown in Figure 8, for instance, the need to retrofit against shear the deck of an arch bridge designed by Christian Menn in the early 1960s led the engineer commissioned to propose several reinforcement variants: (1) vertical steel rods anchored in the deck slab and in steel sleepers under the deck; (2) longitudinal steel girders under the deck; (3) addition of intermediate piers to reduce spans; (4) an under-spanned system applied under the deck and (5) concreting large capitals under the deck in the area near the piers. Each of these interventions would have had a considerable visual impact on a bridge of very high quality, designed by one of the greatest bridge designers of his generation, and which represents a fine example of the art of building in the early 1960s. For this reason, the owner searched for a second opinion and called for other less architecturally invasive solutions to be proposed. It was against this backdrop that we were able to propose and carry out a strengthening that was very respectful from an architectural point of view. The new shear reinforcement is made up of post-installed reinforcing bars embedded in inclined boreholes. The anchor heads were sealed with mortar, so that the strengthening work is barely visible once completed. By using a new technique, developed in collaboration with a specialized company, it was possible to propose a method that respects the existing structure.

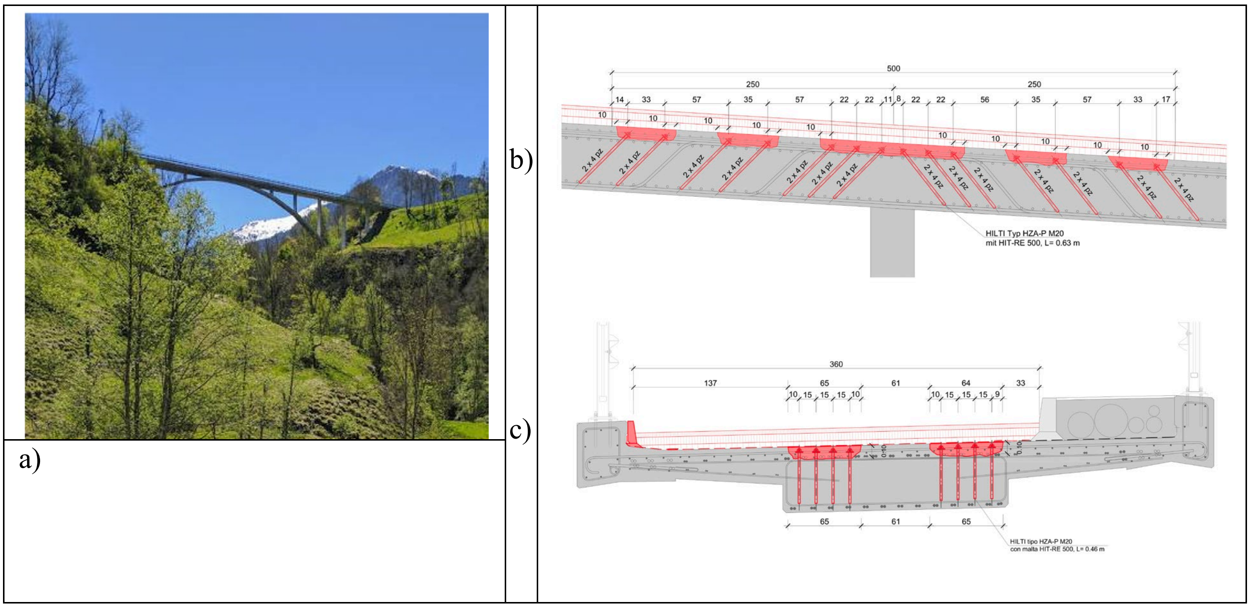


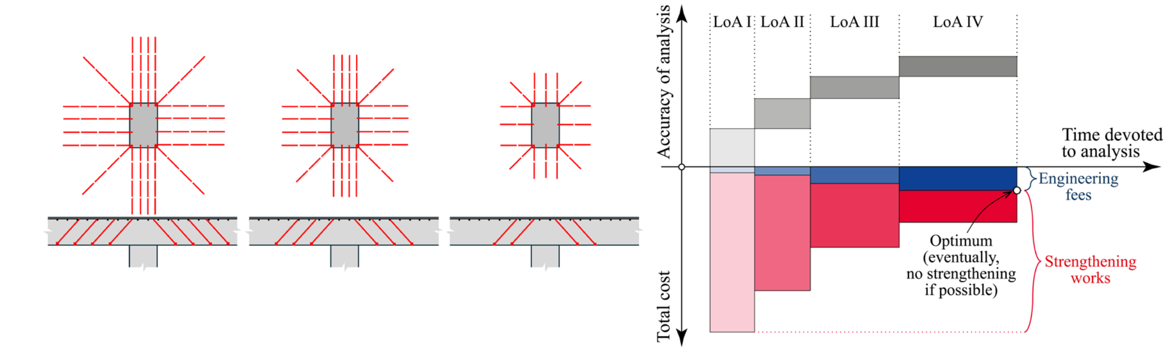
Figure 8. Valserrhein bridge Uors-Surcasti in the Swiss Alps; (a) view of the bridge designed by Christian Menn, 1962; (b) longitudinal section and (c) cross section of the deck showing the strengthening details (Lurati Muttoni Partner, 2022).

Analysis, dimensioning, and assessment: new vs. existing structures

In the example shown above, the quantity of post-installed reinforcement could be greatly reduced by using detailed verification methods. This situation is well known and occurs frequently. This means that the methods of analysis, dimensioning and verification should be adapted to the engineer's task. This is not necessarily specific to existing structures. For new structures too, it is always reasonable to start with approaches and calculations that are as simple as possible, and to refine them only when this is necessary or can lead to an optimisation of the resulting project.

It is to account for this matter of fact that the so-called levels of approximation (LoA) approach was introduced in standards (we speak of levels of approximation, and not levels of refinement, because we start from the idea that all calculations by the engineer are always an approximation of reality). The idea is very simple and actually corresponds to what engineers with sufficient experience have always done: they first start with a very simplified but sufficiently conservative calculation. If one realises that in any case the verification is satisfied (for example because the failure mode underlying the verification is not governing), or if in any case the economic impact of the conservative verification is limited, one can stop the calculation after the first level of approximation (LoA I) and move on.

If, on the other hand, when dimensioning a new structure, the necessary dimensions (e.g., concrete thicknesses or the required amount of reinforcement and/or prestressing) are too important, then it may be reasonable to move to a higher LoA. The same applies to the assessment of an existing structure: if low LoAs show that structural strengthening is necessary, it is worthwhile to move to higher LoAs that perhaps allow it to be demonstrated that a strengthening is not necessary. Moreover, even if this is still indispensable, the use of higher LoAs for sizing the strengthening can result in considerable savings (Figure 9).



(a) LoA II
80 post-installed rebars

(b) LoA III
60 post-installed rebars

(c) LoA IV
32 post-installed rebars

(d)

Figure 9. Strengthening necessary to ensure the safety level with respect to punching shear in a slab-column connection, applying the LoA (a) II, (b) III, (c) IV and (d) accuracy of the verification and costs associated with re-quired strengthening works as a function of the required time for analyses for different levels of approximation (LoA) (adapted from [19, 20]).

Despite the fact that this approach has been used by engineers implicitly since time immemorial, it was first implemented explicitly in a standard only some 20 years ago at national level [20], then adopted internationally in the *fib* MC2010 [21] and more systematically in the *fib* MC2020 [8] and in the second generation of the European Standard for concrete structures [9] (although not using explicitly the term “Level of Approximation” in the latter).

For critical existing structures, the more refined and general model will be used (higher levels of approximation), whereas for the design of simple new structures, in the vast majority of cases, the use of a simplified version of the model is sufficient (low levels of approximation). In this context, a misunderstanding must be avoided: the statement '*low levels of approximation for new structures and higher levels of approximation for existing structures*' is incorrect. Even in the assessment of existing structures, one will always start with the lowest levels of approximation, either because perhaps such a verification shows a sufficient level of safety (and then the verification stops there), or because the level of knowledge of the structure is too low, and then it is wiser to invest the time in on-site investigations rather than perhaps unnecessary verifications. High levels of approximation are only justified in existing structures when they allow avoiding expensive interventions or limit their cost [19]. On the other hand, high levels of approximation may also be justified for new structures, e.g., when they allow complex cases to be solved, very important structures to be dimensioned, or for economy when the number and repetitiveness of structural elements justifies it.

About research vs. practice and research vs. design

It is a matter of fact that the gap between research and practice (and between research and education as well as between education and practice) has increased significantly in the last decades. The reason seems to be evident: universities are ranked mostly based on the quantification of their scientific production, increasing the pressure over researchers to publish (*publish or perish*). In addition, in an increasing number of universities, new professors are selected mostly based on their (quantitative) scientific production or their potential to succeed in the field, making young professors to be comprehensively more motivated to publish than to invest their time in teaching or in professional and standardization activities. This system means that the most important skills for a young professor today are those of a science journalist (ability to quickly produce good quality texts describing the results of research) rather than those of a researcher capable of producing new ideas. Furthermore, the generation of professors which has been appointed with these criteria is more and more involved in the selection process of new colleagues and will tend to perpetuate the system.

In some universities, in an attempt to solve the problem resulting from the lack of knowledge of some young colleagues on the practical realities, teaching is delegated to colleagues who are essentially active in practice, but not or very little involved in research (professors of practice). This is a false good solution: it presents an increased risk of further segregation between teaching and research, which should, in an ideal situation, be mutually enriching.

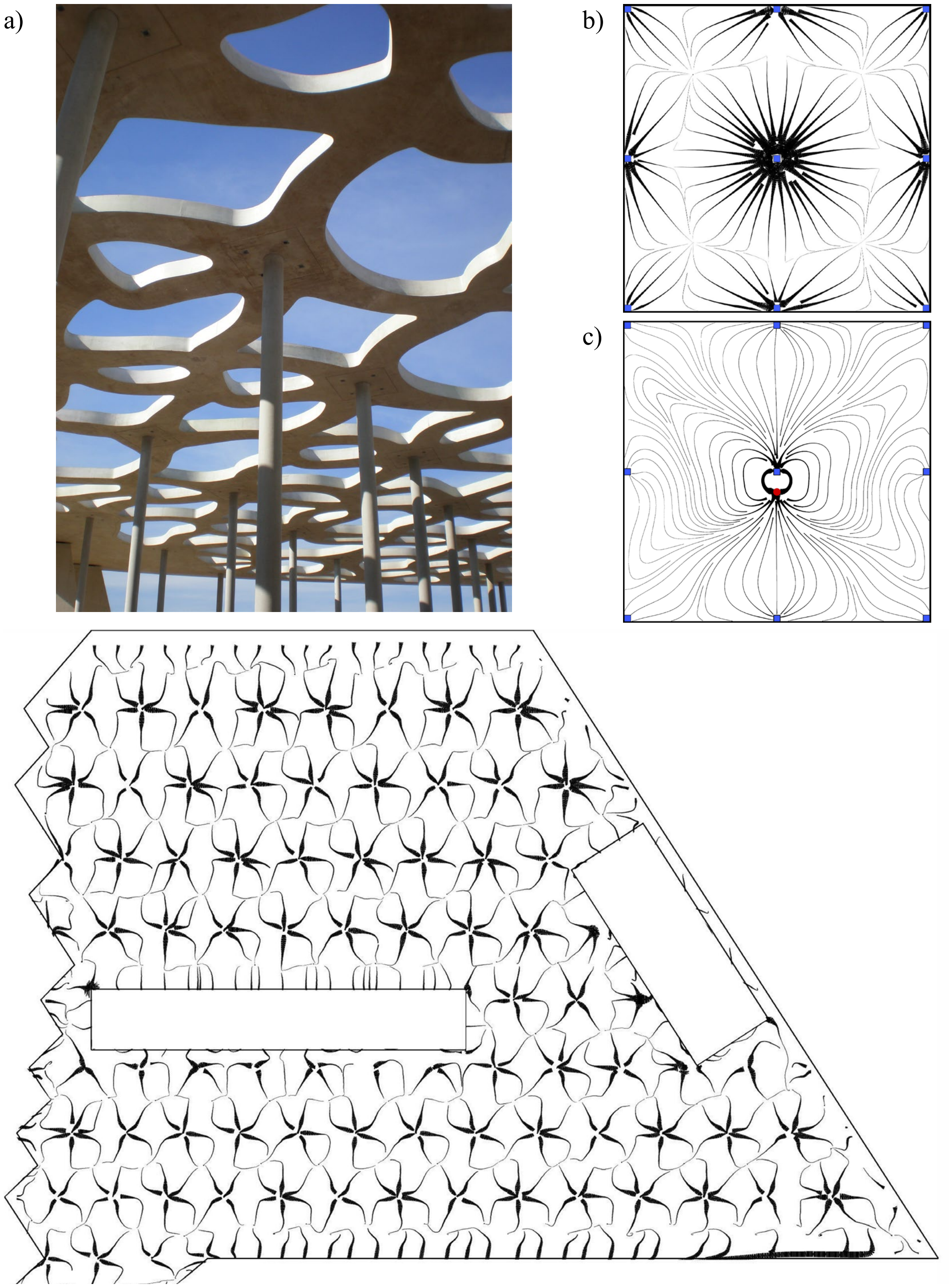
Starting from the pessimistic reading in the previous paragraph, it is necessary to find ways out. Again, one must start from the reading of the situation in order to be able to propose promising solutions. Publications of research results are unfortunately seen as the most obvious outcome of research, but in this respect, there is a flagrant confusion between ends and means. One should publish to disseminate knowledge and the result of research. Thus, publication is nothing more than a means to an end, which is to increase knowledge and, in our case, to improve our structures in terms of economy, reliability, constructability and sustainability.

Another important issue concerns the interaction between design and research. On the one hand, design and practice, as mentioned earlier, should influence structural engineering research, especially with regard to research topics. On the other hand, research also has an influence on the projects, in terms of analysis, dimensioning, choice of materials and other essential points. This influence takes place in structural engineering mainly through standards. In addition, research can also contribute to new structural solutions or the tools derived from research can help to find structural forms that are more efficient and more in keeping with the actual behaviour of the chosen material. This is for instance the case of the project shown in Figure 10.

The architectural idea behind this project was to suspend from a canopy covering an area of around 6000 m^2 the small houses that accommodate the writers in residence at the foundation. This structure therefore forms the suspension points for the small houses, but also has the function of creating a space that links them to the library, an exhibition room, an auditorium, and the common services. For the canopy, the designers (architects and engineers) hesitated a great deal between a grid of beams and a perforated slab: neither of these solutions could adequately meet the challenges of the project. After lengthy discussions, the designers came up with a new structure (neither a perforated slab nor a grid of beams). The material (in this case concrete) is arranged according to the trajectories that follow in a slab the application of loads toward the supports formed by a forest of tall, slender columns. This is the result of research carried out by the structural designer since the 1980s into the actual behaviour of slabs and the analogies with shells. In fact, in slabs, it is possible to trace shear fields (the main direction of the shear force) which represent in fact the path of the loads to the supports. For simple cases (see the uniformly loaded flat slab supported on nine points shown in Figure 10b), the shear field is fairly predictable (the loads converge directly towards the supports). On the contrary, for slightly more complex situations, the shear field describes intriguing paths that may even seem counter-intuitive (see for example Figure 10c with the same slab loaded by a single concentrated load near to the centre column). For the Jan Michalski foundation canopy, we therefore calculated the shear field of a solid slab (Figure 10d) and arranged the material of the new structure along the paths followed by the loads. The result is a structure that highlights the central position of the support columns towards which the ribs converge (and which also support the suspended houses), but which does not show a grid that would be inconsistent with the architectural idea.

This is an interesting example where not only the shape, but the structural system also can be generated to better meet the architectural challenges from considerations how the structure works. It is also a nice example where a creative work is issued from research in structural engineering as well as from intensive discussions between the architect and the structural designer.

a) b) c)



d)

Figure 10. (a) Canopy of the Jan Michalski Foundation dedicated to writing and literature at Montricher, Switzerland; (b) shear field for a flat slab under uniformly distributed load and (c) under a concentrated load near to the internal column; and (d) shear field of the canopy (with Mangeat-Wahlen architects, Muttoni and Fernández civil engineers, A. Muttoni structural designer) [22].

Why are standards more and more complex, and what can we do to avoid them being difficult to use?

"*Standards are more and more complex, uneasy to use, and lead to more and more uneconomic structures*": this is a statement that we often hear and perhaps also share. Does it correspond to reality? what is the reason? How do we get out of it?

It is a matter of fact that standards are becoming increasingly complex and exhaustive. Figure 11 shows the evolution of the number of pages of the Swiss standard for concrete structures since its first edition in 1903. In comparison, the number of pages of the same European standard is also shown. It is interesting to note that when, in the 1930s, the number of pages doubled (from 12 to 24), the famous engineer Robert Maillart made the following comments [1]:

> *"Unfortunately, the provisions of the standards mislead engineers or force them to apply them mechanically, particularly when they are used during the training of engineers and when they are imposed by control officers. A general relaxation of the rules, giving greater responsibility to the engineer, would go a long way towards improving the quality of our buildings. Simple design is also possible and sufficient. The rational evaluation of its results leads to structures with an identical and uniform level of safety compared to those designed by the thoughtless application of building standards considering all their details."*

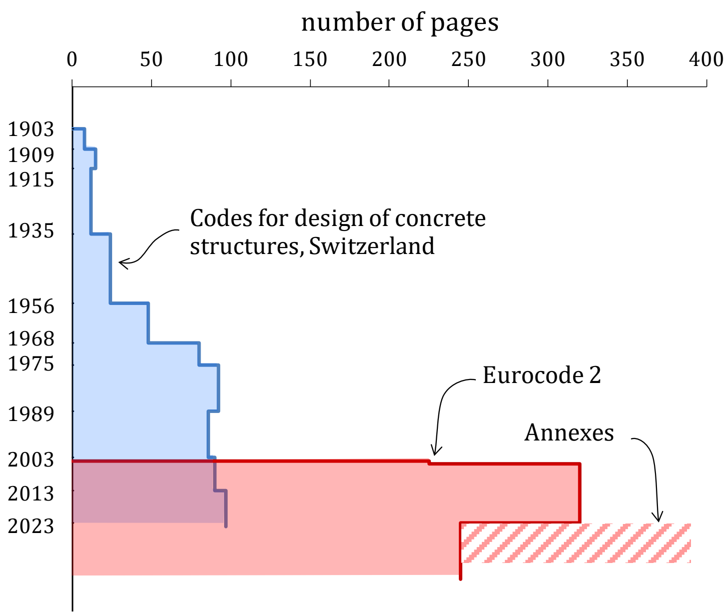
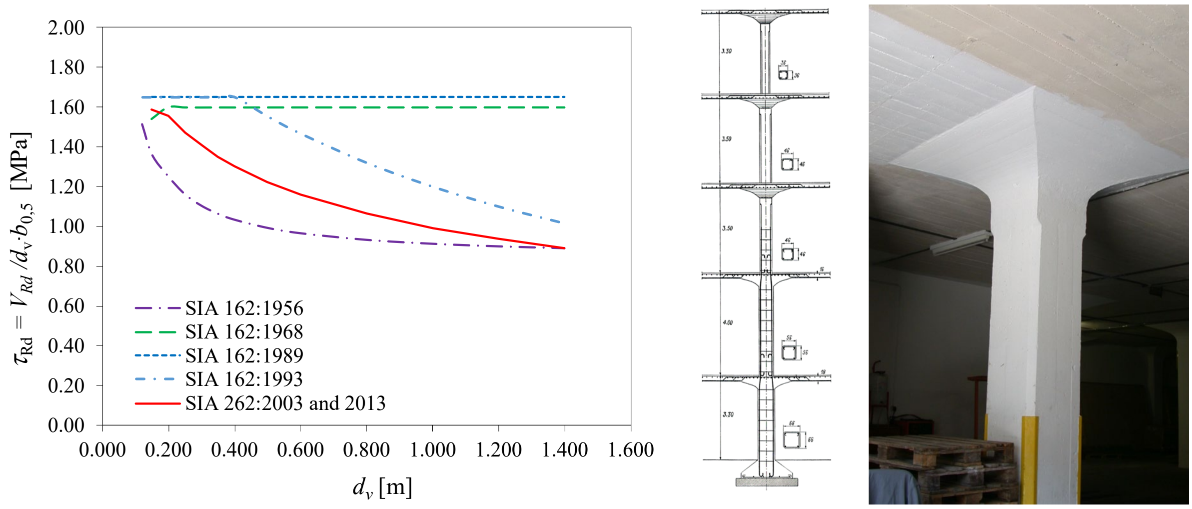


Figure 11. Evolution of number of pages of the Swiss standard for concrete structures and the equivalent Eurocode (adapted from [20])

What would Robert Maillart say today? Was he right? Before answering these questions, it is also useful to understand the reasons for these changes.

Let's start with the fact that current standards are often more conservative (and potentially less economic) than those of a few decades ago. Figure 12a shows the example of the punching resistance of reinforced concrete slabs according to Swiss standards, from 1956 until the latest edition in 2013. Firstly, how did Swiss engineers do it before 1956, when the 1903 and 1935 standards did not even mention punching? The answer is simple, the shape of the capitals over supporting columns was defined in such a way as to limit shear stresses around the column (the Maillard capitals shown in Figures 12b and c had a hyperbolic shape, for example, so as to keep the shear stress constant regardless of the distance from the column axis) while in foundation slabs, when it was not possible to vary the thickness of the slab, bent up bars were placed to effectively carry the shear forces. From the 1950s onwards, it was thought to simplify the construction methods (flat floors and no more bent up bars): the problem of shear and punching in columns supported slabs was thus created out of nothing and had to be dealt with in the standards. For beam shear, Ritter and Mörsch had already proposed models and solutions more than a century ago, but for punching, the problem is more complex, so it was essential to calibrate empirical formulae or models (as it is today) by means of laboratory tests. To limit the cost of punching tests, it was decided to test only the part of the plate subjected to hogging moments, and the thickness was limited to avoid too large specimens and too high forces involved, thus implicitly creating two problems: the membrane effect was neglected (on the side of safety), and the size effect was not accounted for (it is now known that it is not on the side of safety at all). In addition, one wanted to test shear, not bending, so the tests of those years were conducted on elements that were heavily reinforced in bending. It is interesting to note in figure 12a that all editions of the Swiss standard gave practically the same punching resistance for thin slabs (this is no coincidence, they were calibrated on the same slabs). Furthermore, the first 1956 standard already had a kind of size effect, but this was purely by chance. In fact, at that time, it was based on the idea that the shear resistance depends on the thickness of the plate *h*, and not on the effective depth *d*, so that as the thickness increases, the *h*/*d* ratio decreases and there is therefore a reduction in strength when normalising it to the effective depth (this effect was further enhanced in the Swiss standard of 1956 by considering the control perimeter at a distance *h* from the column edge). In the years that followed, however, it was rightly decided to consider the effective depth *d* for the calculation of resistance, but without considering the size effect, simply because it was not yet known for reinforced concrete structures, or because since in the 1970s there have been doubts as to its relevance for practical cases.



a) b) c)

Figure 12. (a) normalized punching shear resistance as a function of the effective depth according to the Swiss codes since 1956 (f_{ck} = 30 MPa, c/d = 1.25, ρ = 0.75%); (b) mushrooms slabs with capitals according to Maillart and (c) Magazzini Generali at Chiasso Switzerland, 1924-25.

When it was finally realised that the size effect and the reduction in resistance for poorly reinforced slabs should be accounted for, there were two possibilities for the following standards: either a very simple formulation is maintained by calibrating it for thick lightly reinforced slabs (which would, however, be overly conservative and give uneconomical solutions for thin slabs or/and highly reinforced in bending), or a necessarily more complex formulation is sought that can account for the majority of cases found in practice. In most cases, the latter solution has been chosen, or with some compromises, explaining the fact that in some cases, codes are overly conservative.

Figure 12 highlights yet another problem: thick flat slabs and footings built in Switzerland between 1968 and 2003, and especially up to 1993, are potentially unsafe in relation to today's knowledge. This means that for the assessment of existing structures, it is useful to have more refined calculation methods than those used for the dimensioning of new structures if one wants to avoid systematically carrying out costly retrofitting's. This explains the resurgence of research into punching, and shear in general, over the last three decades or so (P. Regan, for example, asked the rhetorical question "*Research on shear: a benefit to humanity or a waste of time?*" to explain this in 1993 [23]). It was in this context, for example, but also to account in a more rational manner for the size effect and the influence on punching resistance of a low level of flexural reinforcement, that the author of these lines developed the Critical Shear Crack Theory from 1985 onwards [24, 25, 26], subsequently implemented in several national [27] and international standards [21, 8, 9] (research in this field was subsequently carried out even more intensively, see [28] for an overview, after being confronted with several tragic accidents, as it will be shown later, see Figure 13, [29, 30, 31]).

The same story about an increase in complexity and supposed conservativeness could be told for other standards and for other cases (shear of slabs without shear reinforcement, shear of prestressed beams, anchorage length and laps of reinforcement bars, etc).

To return to Maillart's concerns, we should not forget that he was writing in the 1930s, addressing engineers of a small country, when civil engineers had a rather uniform and high level of training, when the problems to be solved were simpler and more homogeneous, and when the level of knowledge was certainly less developed. In addition, a fundamental difference compared to today is that, because of their more limited knowledge and a society with fewer constraints, engineers took on much more responsibility and relied more on what we call "common sense" or "engineering judgement". Today, the situation has changed dramatically: taking responsibility for deviations from a standard is less and less common (also because the consequences of potential problems have become more severe) and at the same time, some engineers do not hesitate to go to the limit of what is allowed by a standard, even when this does not make much sense (this is rather justified by some level of unconsciousness related to the lack of knowledge of the limitations of the current standards). This means that more and more limits and cases have to be defined and treated in the standards.

While we can certainly feel a certain nostalgia for the freedom engineers enjoyed at Maillart's time, we must bear in mind that our standards are aimed at a multitude of users (it is estimated that half a million engineers will use the Eurocodes in a near future) who operate in very different situations.

When we began working on the 2nd generation of the Eurocode for concrete structures (the author of these lines chaired the working group that drafted the main part) [9], one of the main aims was to improve the ease of use of the standard, and in this context, we asked ourselves the following question: should this standard be able to resolve 80-90% of cases in a simple manner, or should it be able to resolve a large proportion of the cases that engineers are faced with today? The answer is not easy: in the first case, the use of the standard would be easier for most cases, but would enormously complicate the work of engineers, who would often have to deal with situations not considered in the standard. Finally, we have once again come to the conclusion that the approach based on levels of approximation enables ordinary cases to be solved simply, and more unusual cases to be solved in a way that is inevitably more complex.

To be effectively effective, the Levels of Approximation Approach (LoAA) needs proper implementation in standards. In fact, it is crucial that when an engineer moves from one LoA to the following one, an important part of the calculation can be kept unchanged. Ideally, it is necessary that at each step, only certain parameters are refined. Therefore, care must be taken in the derivation of the code provisions: it is necessary to start with the general model at the highest level, and then to simplify the equations at lower levels as we go along, ensuring that certain parameters are not calculated from the beginning, but chosen on the basis of different considerations.

What are the disadvantages of this approach? Firstly, freedom is given to the designer (the standard is therefore less prescriptive, which can also be seen as an advantage by many). For example, some colleagues fear that the client will always demand the highest LoA, in the sense that this is often their interest when fees are fixed (see figure 9d). On the other hand, this fear depends on the type of contract the designer has and the importance he wants and can give to common sense in these considerations. It is therefore essentially for this reason that the 2nd generation of Eurocode 2 [9] does not explicitly mention the concept of Levels of Approximation but is nevertheless formulated to allow such an approach.

Another disadvantage of the method is that with the LoAA, standards become longer (since there is a repletion of provisions on the same content) and, at first sight, more complex and more difficult to use. Nevertheless, this is only the first impression, and the reality is exactly the opposite: the LoAA is, once the method is understood, extremely effective in reducing calculation time in the vast majority of cases and allowing the study of cases that cannot be investigated with too general or concise standards.

Another advantage of being able to carry out an initial check in a simplified way relates to the reliability of our work and the probability of making calculation errors. The latter is a real concern, if we think, for example, of the increasingly limited time available for analysis and verification. If we look again at the Figure 2 and consider the trend over the last few decades, we can only conclude that other activities, such as coordination, meetings, communications, and the drafting of documents that are not always essential, are taking up more and more time. Deadlines are also getting shorter and shorter, and the likelihood of misunderstandings is increasing due to the increasingly complex way in which projects are organised. In addition, experienced engineers have less and less time to devote to the supervision and accompaniment of their younger colleagues, who in turn are increasingly using complex and sophisticated tools that are not always transparent or fully mastered, so the likelihood of error increases. In this context, we should not forget that, if it is true that a serious problem on site or the collapse of a structure is often the result of the accumulation of several errors, it is also true that calculation errors often represent a significant proportion of the causes of a collapse (Figure 13).

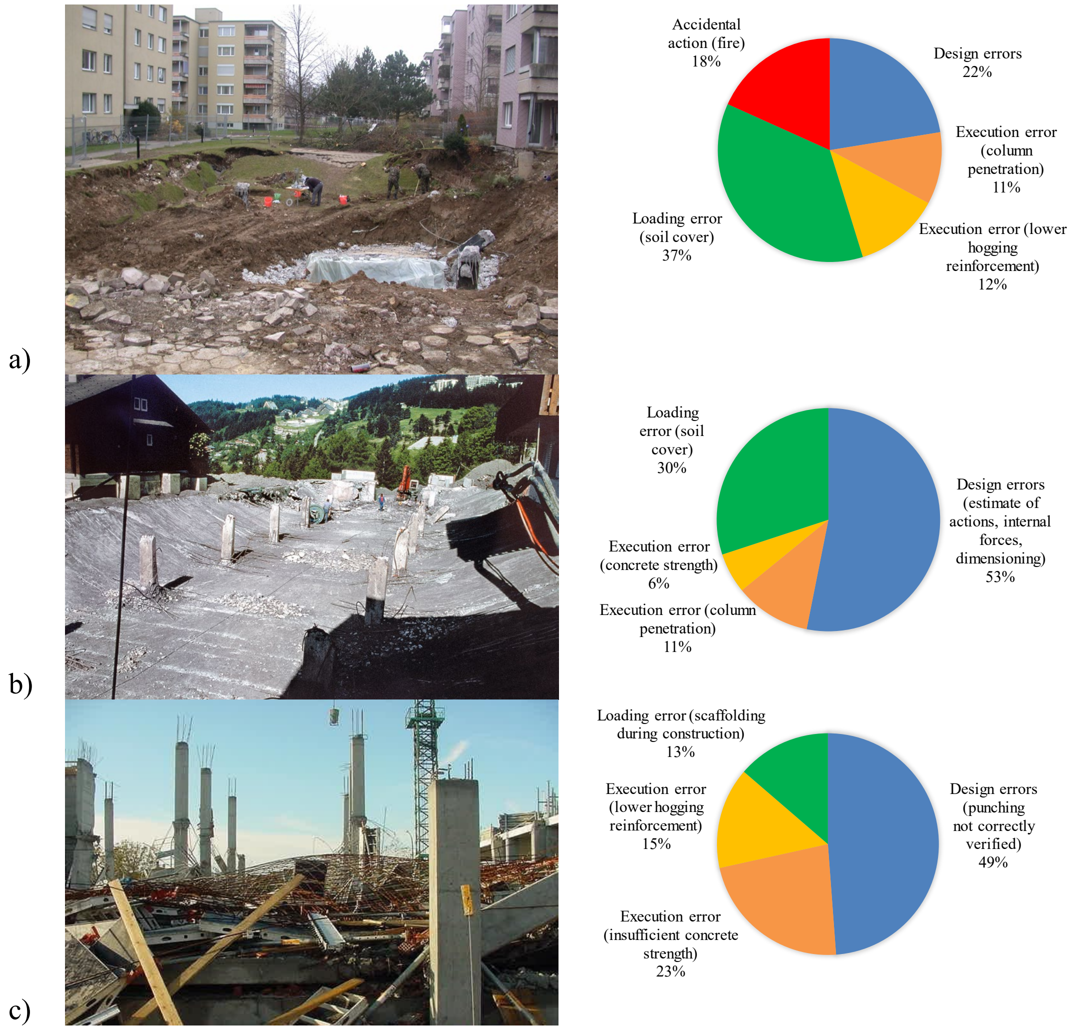


Figure 13. Quantification of the causes of collapses due to punching: (a) Gretzenbach accident in Switzerland, 2004 [29]; (b) Bluche Accident in Switzerland, 1981 [30]; and (c) Cagliari Accident in Italy, 2004 [31].

For all these reasons, refined methods are needed to solve today's problems, for example in the efficient assessment of existing structures, but at the same time, having simple and easily understandable tools is essential to limit risks and save time that can be devoted preferably to quality design.

Conclusion

Based on the author's experience and observing the evolution of the profession over the past decades, today's situation has several unsatisfactory aspects. In this context, the strong commitment of schools and professional organisations is necessary to make structural engineering more attractive to the younger generation, but not sufficient. A great deal also depends on the examples we set and pass on to the younger generation, and this depends essentially on the activity and attitude of every one of us.

The main thesis of this contribution is that the intellectual and creative component of structural engineering should be more emphasized and gain more attention.

References

[1] Maillart R. (1938), Current issues in reinforced concrete construction (in German: Aktuelle Fragen des Eisenbetonbaues), Schweizerische Bauzeitung, Zurich, Switzerland
[2] Nervi P. L. (1945), Scienza o Arte del costruire? , Edizioni della Bussola, Rome, Italy
[3] Freyssinet E. (1993), Un amour sans limite, Collection of writings 1936-1958, Editions du Linteau, Paris, France
[4] Torroja E. (1957), Razón y Ser de los Tipos Estructurales
[5] Schlaich, J. (1992), Can Conceptual design be taught?, The Structural Engineer
[6] Muttoni, A., The Art of Structures (2011), EPFL Press, Lausanne, Switzerland
[7] Wikipedia, https://en.wikipedia.org/wiki/Engineer (accessed 10.05.2024)
[8] fib Model Code for Concrete Structures (2023)
[9] CEN (2023), EN 1992-1-1, Eurocode 2 - Design of concrete structures - Part 1-1: General rules and rules for buildings, bridges and civil engineering structures
[10] Conceptual Design of Structures (1996), Proceedings of the International Symposium, University of Stuttgart / International Association for Shell and Spatial Structures
[11] Muttoni A. and Schwartz J. (2024), Conceptual design of structures in practice, research, and teaching, chapter of the book “Conceptual design of structures”, Birkhäuser publishing
[12] Muttoni A., Lurati F., Muttoni L., Rezzonico M. (2022), Two bridges in southern Switzerland with under-spanned concrete girders, Structural Concrete in Switzerland, Swiss report for the fib Congress in Oslo, Norway.
[13] Muttoni A. (1997), Bridges with an innovative system (in German: Brücken mit einem innovativen statischen System», Schweizer Ingenieur und Architekt, Zurich
[14] Lázaro L., Domingo A., Abel J., Kawaguchi K., Gantes C. (2021) Mamoru Kawaguchi, Innovation and Tradition in Structural Design, International Association for Shell and Spatial Structures
[15] Muttoni A., Lurati F. (2023), Under-spanned bridges: a suitable solution for efficiency and sustainability, Proceedings of the *fib* Conceptual design symposium, Oslo, Norway
[16] Muttoni A., Schwartz J., Thürlimann B. (1996), Design of Concrete Structures with Stress Fields, Springer Science & Business Media.
[17] Muttoni A., Muttoni L., Lurati F. (2010), The new bridge at Frasco over the Verzasca River, Structural Concrete in Switzerland, Swiss report for the fib Congress in Washington DC, USA.
[18] Engineering Structures on National Roads as Cultural Assets (2023) (in French : Les Ouvrages d’Art des Routes Nationales en qualité de Bien Culturels), Guidline of the Swiss Federal Road Administration

[19] Muttoni A., Lurati F., Faria D., Simões J., Fernández M. (2023), Assessment of Existing Bridges: The Swiss Experience of the Last Three Decades, Proceedings of Italian Concrete Conference 2022, DOI: 10.1007/978-3-031-43102-9_38
[20] Muttoni A. (2003), Introduction to the Swiss Code SIA 262 (in French and German), Documentation SIA, Swiss Society of Engineers and Architects SIA, Zurich, p. 5-9.
[21] fib Model Code for Concrete Structures 2010 (2013)
[22] Muttoni A., Fernandez Ruiz M. (2014), Concrete Canopy of "Maison de l'Ecriture" in Montricher, Structural Concrete in Switzerland, Swiss report for the fib Congress in Mumbai, India.
[23] Regan P.E. (1993), Research on shear: a benefit to humanity or a waste of time?, The Structural Engineer
[24] Muttoni A. and Schwartz J. (1991), Behaviour of beams and punching in slabs without shear reinforcement, Proceeding of the IABSE Colloq., Stuttgart, Germany.
[25] Muttoni A. (2003), Shear and punching strength of slabs without shear reinforcement, Bet. Stahlbetonbau, [in German].
[26] Muttoni A. (2008), Punching shear strength of reinforced concrete slabs without transverse reinforcement, ACI Struct. J.
[27] Swiss Society of Engineers and Architects (2003), Code 262 for Concrete Structures.
[28] Muttoni A., Simões J.T. (2023), Shear and punching shear according to the Critical Shear Crack Theory: background, recent developments and integration in codes, IBRACON Structures and Materials Journal.
[29] Muttoni A., Fürst A., Hunkeler F. (2005), Slab collapse of the undergound garage Standenacker in Gretzenbach, Published Report (in German: Deckeneinsturz der Tiefgarage am Staldenacker in Gretzenbach)
[30] Guandalini S., Muttoni A. (2008), Study of the collapse of a car park slab, in "Structural safety of covered car parks" (in French: Sécurité structurale des parkings couverts), Document D02226, Swiss Society of Engineers and Architects, Zurich, Switzerland
[31] Muttoni A. (2009), Investigation of the collapse of the structure of a shopping centre in Selargius (Cagliari, Italy) on 28 October 2004, unpublished report

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