Structural designs that required thinking
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Abstract. We discussed the peculiarities of three structural projects. The \textit{El Ferdan swing bridge} over the Suez Canal, the longest in the world, required the optimization of structural weight and deflection, pursued with genetic algorithms. The \textit{Museum of the Future} in Dubai, is supported by a single-layer steel gridshell following a pseudo-toroidal double-curvature surface, which required the optimization of a great number of diagrid nodes, parametrically designed with a custom tool. The competition-winner project for the new \textit{Stadio Milano} follows the vision of a Gothic Cathedral with slender buttresses, tall multi-storey arched frames, all covered by a first-class cable-supported glazed facade, which fulfills the clean “glass-box” architectural intent. Although very sophisticated calculation tools are available, these experiences suggest that the human contribution of the structural engineer is still, at least for now, of paramount importance.

Introduction
Advancements in numerical structural analysis have freed the engineer from the burden of calculations. Buildings and bridges of rare beauty, that thirty years ago could not have been conceived due to the difficulties in the calculations, are now reality. We are witnessing an actual Renaissance in structural engineering, to carry out the finest futuristic designs by imaginative architects. At the same time, we assist at the definition of increasingly complex technical regulations and standards: even the simplest structures (regular frames, truss bridges) shall comply with long verification formulas, where each uncertainty carries a coefficient, to be somehow calibrated. At the same time, the paradigm of artificial intelligence suggests that everything can be dealt with automatically, via modern calculation tools, making the human contribution of the structural engineer the basic knowledge of structural mechanics superfluous. Does all this contribute to the Renaissance trend? On the one hand, the engineer is hindered in creative design, because the counterintuitive complexity of the rule, which can only be pursed with a numerical approach, prevents a synthetic vision: the structure is not governed, but governs! On the other hand, standards and codes are of little help, if not an obstacle, for complex or innovative designs, whereas the automatic decision making approach cannot fulfill all the requirements. Here we humbly present a few structures we know well enough from working on them, with the aim of highlighting the problems and the scientific advancements (modeling, structural optimization, customized parametric approach) they required, which could not be completely solved by standards and automatized numerical tools.

The swing bridges over the Suez Canal
The project for the two double swing bridges at El Ferdan, Ismailia over the Suez Canal [en.wikipedia.org/wiki/El_Ferdan_Railway_Bridge] consists in the retrofitting and upgrading of the existing bridge from one to double rail lane, and in the design of a new double-rail lane bridge, with geometry similar to the existing one. With a total length of 640 m, and a 340 m span between
the central piers, this is the longest swing bridge in the world. Fig. 1(a) shows half portion of the new bridge in the rotated configuration. This is a metallic truss structure, assembled by welding on the bank of the canal as represented in Fig. 1(b). The design included the mechanical rotation and its locking system through electrical motors and hydraulic pistons. A detail of the cylindrical hinge with rollers that permit the rotation of the two halves of the bridge is indicated in Fig. 1(c).

For a bridge of this type, it is of paramount importance to minimize the weight, to facilitate the movement, as well as the deflection, both in the “open” and “closed” configurations, to fit the constraints. Derivative-free genetic optimization algorithms were implemented for minimum weight (objective 1) and minimum displacement (objective 2). These objectives are in contrast one other: to obtain the minimum weight the structure should be as thin as possible, but to reduce the displacement, the structure has to be strengthened.

Fig. 1. The new swing bridges at El Ferdan over the Suez Canal. (a) View of half portion of the completed bridge in the rotated configuration. (b) The bridge during the construction phase on the bank of the canal. (c) Detail of the cylindrical hinge with rollers that permits the rotation.

Genetic algorithms are based on principles of natural genetics and selection. In derivate-free algorithms [1], to find the optimum it is not required to calculate the derivative of the fitness function, which is in general hard to define. The typical procedure is based on: a starting population of individuals (usually a “preset” configuration defined by experience is used as a starting point); each point is characterized by a set of variables, composing the pool of genes of each individual; objective functions are evaluated for each individual to obtain the fitness; a new generation is defined and includes the best individuals from the previous population and new individuals generated with reproduction, crossover and mutation techniques; objective function are evaluated
for each new individual; new generations are defined up to convergence. For the case at hand, following [2] and [3], the workflow consisted in: 1) creation of FEM model based on the starting geometry; 2) random increment of area for each structural element to create a new individual; 3) structural analysis of this new individual from point 2; 4) determination of fitness functions for each individual; 5) use of the genetic algorithm to define the new individuals based on the elitism, mutation and crossover between different genes; 6) structural analysis of this new individuals from point 5; 7) iteration from point 4 to 6 until the optimal solution is reached. The software chosen for the parametric structural analysis is Grasshopper associated with SAP2000.

Fig 2(a) describes, in the plane total weight vs. vertical displacement, the results of the first generation: the initial condition, corresponding to the configuration of Fig. 2(c) is highlighted as a red dot. The other points are the results of the structural analysis for random increments of the variables, represented by the area of each truss element. Observe in the graphs the Pareto Front, i.e., the locus of points of solution that dominate all the other solutions (dominant solutions).

The typical analysis for each population is made on 60 individuals, subjected to a set of constraints (structural verification according to Egyptian codes, cost reliability-interaction [4]). Fig. 2(b) shows the distribution of fitness function for the successive generations, where each dot is associated with one individual. The first generation is represented by the blue dots on the right-hand-side of the graph. Following generations show that the genetic algorithm provides new individuals (genetic evolution of genes) with solutions better than the previous ones. The evolutive trend is clearly visible, because the Pareto front moves leftwards. The latest generation gives individuals placed on the best pareto front: part of them optimizes weight and the others minimize displacements and members ratio. The selected solution, after many simulations and verification, is represented in Fig. 2(d), with indication of the area increments with respect to the initial condition of Fig. 2(c). The results were systematically compared with hand-made optimization, in order to corroborate the results obtained with the complex genetic algorithm.
The Museum of the Future in Dubai

The Museum of the Future [en.wikipedia.org/wiki/Museum_of_the_Future] in Dubai, UAE, shown in Fig. 3(a), is a multistorey building, with steel-RC composite floors and steel floor trusses supported by following the feature pseudo-toroidal double-curvature surface; additional lateral stiffness is provided by an internal RC core. The tubular truss of the shell is visible in photograph of Fig. 3(b), taken before the installation of the metallic cladding.

![Fig. 3. Museum of the Future in Dubai. (a) The completed building and (b) the tubular truss structure before the installation of the metallic cladding. (c) The model for the definition of the geometry of the nodes and (d) their assembly during the construction phase.](image)

The steelwork connections and the construction method were designed by analyzing the staged erection sequence, to meet the specified construction tolerances and to allow for the effect of the lock-in forces into the connections and members design. This included the optimization of the diagrid nodes in order to minimize the use of internal stiffeners and simplify the steel-contractor manufacturing operations. Since all nodes are different one another (different geometries, pipes and internal actions), more than 800 FEM models had to be developed, by using a dedicated internal parametric tool developed in Grasshopper [5]. Fig. 3(c) indicates the model that defines the geometry of the nodes; their assembly during the construction phase is shown in Fig. 3(d).

The new Stadio Milano

The competition-winner design for the new Stadio Milano, shown in Fig. 4(a), was developed following the architectural vision [www.nuovostadiomilano.com/it] of a “Gothic Cathedral”. This is materialized by slender regularly-spaced buttresses and tall multi-storey arched frames, covered by a glass envelope, as per Fig. 4(b). In the structural design the arrangement of the members
intuitively follows the flow of the forces, as in gothic architecture. A modular repetition of the structural frames reduces both the construction costs and the erection time, improving quality.

![Fig. 4. The new Stadio Milano. Rendering of (a) the completed building and (b) detail view of the structure with the glazed curtain wall. (c) Schematic section of the load-bearing structures and (d) details of the cable supported glass façade.](image)

A section of the load bearing structure is shown in Fig. 4(c). A very innovative transparent façade is planned, where the glass panels are supported by a set of vertical stainless steel cables [6], tensioned between the upper buttresses at the roof level, and the lower RC cantilevers at the Galleria Mezzanine level. These synergically contribute to balance, at the roof level, the overturning moment due to the cantilever roof, spanning over the playfield, as well as the large cantilever at the corner of the Galleria Mezzanine (the upward forces from the cables reduce the long-term deflection of the concrete slab). Glass panels are heat-strengthened, stratified with high performance polymers, connected to the cables by custom-designed stainless steel clamped connectors, indicated in Fig. 4(d). Cable supported glazed surfaces have remarkable properties, including blast-resistance capacity [7]. The design will provide the Milan Stadium with a first-class, transparent and elegant glazed facade, to fulfill the clean “glass-box” architectural intent.

**Conclusive remarks**
The design process of the structures discussed here was quite complex, as it required the selection of geometry, static scheme and initial parameters, before proceeding with the structural analysis and verification of the suitability of members and connections. Modern calculation tools allow
structural verifications to be carried out in a very short time on a large number of models, in which the geometry and sections can be varied until an optimal configuration is achieved. Although genetic algorithms based on parametric design tools apparently make it possible to automatically obtain the prefigured target according to the paradigm of the so-called Artificial Intelligence, nothing can replace, at least for now, the skill of a wise structural engineer. The designer has to make a rather difficult decision in selecting a preliminary, albeit rough, solution (preset), among all the possible alternatives, adequately satisfying all the requirements in terms of safety and serviceability imposed by design codes and a number of specified merit criteria such as cost and weight. Human, as opposed to artificial, intelligence is necessary to find an good preset, sufficiently closed to the ideal one, in order to direct the software operations and associated processing (crossover, migration, mutation), not only to reduce the required computation time, but also to reach a reasonable engineering optimum among all possible local optima.

Although it is commonly believed that the use of increasingly complex regulations may suggest universal design rules, these rules can only be used in the verification phase. Only a deep knowledge of structural theory and a wide experience on the really built constructions can allow the extreme synthesis of a complex structure in a simple but significant scheme, verifiable on the basis of elementary formulas, which will guide the preliminary, but necessary, basic choices.

References


