Structural analysis and design of long span suspension bridges with regards to nonlinearities, uncertainties, interactions and sustainability

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ABSTRACT: There is today a strong interest and general commitment toward the quality of the things that engineering is creating. Generally speaking, quality involves and concerns different aspects of the engineering products, like the aesthetics, the ergonomics, the comfort, the structural serviceability, the structural safety and the durability. From this point of view, quality means, at the end, sustainability in the most general sense. All these aspects should be considered in a modern conceptual design of a bridge structure. The structure should be defined taking into account wide criteria and the critical aspects, which give clarity and coherence to the whole structural design, must be strongly pointed out.

1 INTRODUCTION

Speaking about engineering design, one can consider two different design strategies. In the first one, the effects of the design environment are divided into two categories: general loading system and specific loads, for example earthquake. The design solution is searched initially for the first class of loads, and then corrected and improved by some additions. This is the classical application of the dissection techniques for the solution of an engineering problem, with respect to the degree of 1) understanding, 2) uncertainty, 3) modeling, 4) predictability, 5) computability, or, in general, with respect to simple vs. complex systems. It is important to note that, when complexity is neglected, there is the danger of an oversimplification of the problem, with the possibility to find bad solutions. In the second case, instead, one finds the control of all actions by design: all the aspects of the structural problem are considered together, and the synthesis of the design is fully interconnected. It is clear that this design process is more complex, due to the difficulties in handling the problem, from the mechanical point of view and/or from the economical point of view. Of course the coherence of the final design is enhanced, as shown by the lack of asymmetry.

There is today a strong effort to optimize the engineering design by the so-called soft-computing techniques, to tackle all this complexity. This approach, pursued in this research by the Research Unit of the University of Rome "La Sapienza" within *COFIN2002*, is a pervasive orientation of the design (global strategy) to an optimal behavior that starts from the conception of the structure. In the references, one will find the context where, at the same time, this research unit has its cultural basis and toward which will evolve to consider the nonlinearities (Fig.1), the interactions (Fig.2) and the uncertainty previously recognized (Calzona & Bontempi, 2002; Silvestri & Bontempi, 2003; Silvestri, 2002; Smith, I. 2001). This research group in the last three years furthermore takes effective advantage from being strongly involved in the consultant activities related to the design and the analysis of the Messina Strait Bridge.

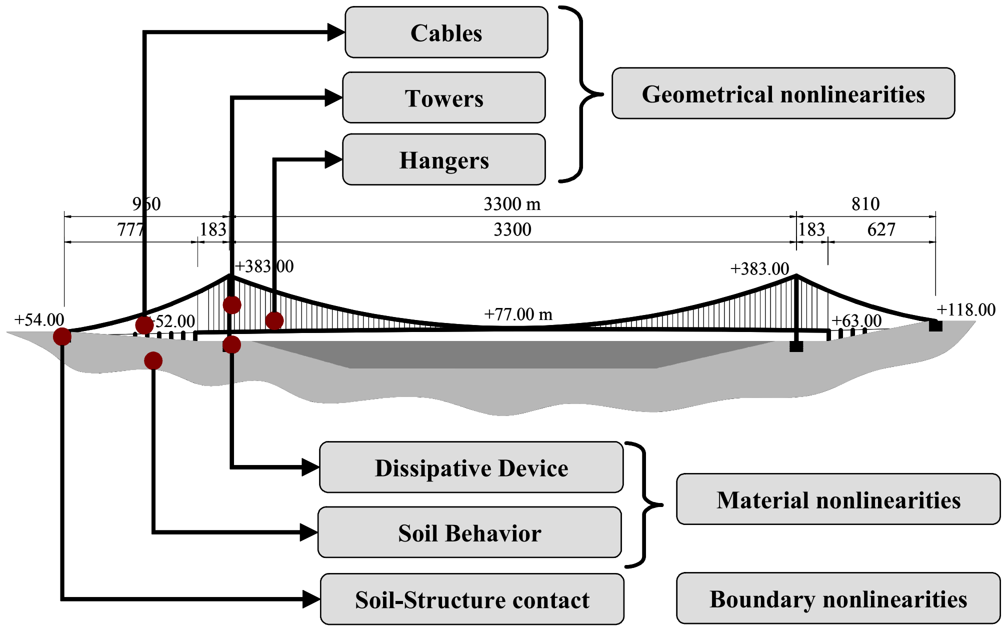


Figure 1. Some relevant nonlinearities considered in the modeling of the long span suspension bridge.

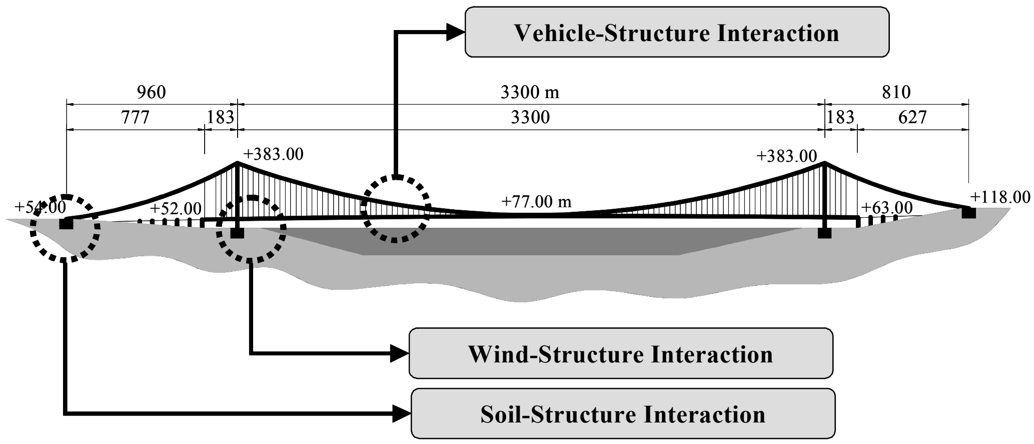


Figure 2. Interaction phenomena considered in the modeling of the long span suspension bridge.

The performance analysis for the evaluation of the reliability of complex structures like the Messina Strait Bridge, generally results from three main points:

1. Formulation of the structural problem and organization of the relevant data and information;
2. Structural modeling and numerical analysis;
3. Synthesis of the results and critical evaluations.

The inherent complexity in planning and designing this kind of structures leads to the necessity of a new design statement in the framework of the so-called Performance-Based Design (*P.B.D.*), which aims at defining preventively and accurately the performances requested to the structure (Fig.4). Absolutely critic it appears the ability to predict the performance required for such structures and the necessity to provide the qualitative and quantitative elements able to support the following decisional processes needed to specifically define such an important structure, including both limit and service behaviors. The performance approach to the structural design is based on the verification of the exact suitability of the structure with respect to fixed requisites (Catallo & Biondini & Bontempi & Frangopol, 2004; Albertini, & Sgambi, & Garavaglia, 2003).

2 STRUCTURAL MODELING

The first point to face concerns the general consideration about all the activities connected with the construction of the model: it was just recalled the central role played by modeling in the overall performance based design. The modeling process consists of a net of theories, decisions, and operative aspects that make possible to extract useful information about the system studied. The existing data and information are organized in the real system model, obtained starting from the reality through a reduction process, maintaining the useful aspects and avoiding to consider the other ones, as schematically quoted on Figure 3: this to end to strictly define the performance characteristics of the structure (Figure 4).

2.1 *The Complexity in the design of long span suspension bridges*

For a long span suspension bridge, like the Messina Bridge, which presents unique and exceptional characteristics, because of complexity of the system (Fig.5), in order to take into consideration all aspects (specifically the critical aspects of Figure 6), it is necessary to adopt a decomposition strategy. In this manner, the structural problem and each relevant aspetcs are hierarchical organized in several levels that can be singularly dealt with. The decomposition can be performed for different aspects: Performance, Structural Organism and Load (Bentley, 1999; Simon, 1980; Perrow, 1999; Fellows, R. & Liu, A. 1997).

It is clear that the decomposition is made for several aspects of the whole structural system, such as design quality, product quality and serviceability. The whole system can be firstly divided into substructures (macro-level), then into components (meso-level), and finally into elements (micro-level). Consequently, it is possible to modify each variable and optimize the structural behavior in order to achieve a specified performance objective (Bontempi & Biondini & Radogna, 2002; Calzona & Bontempi, 2001).

The analysis of a complex structural system hardly can be reduced to a single phase only. Generally in fact there are inside the structure two classes of regions with strongly different mechanical behavior. One considers the so called *B-regions*, where the stress picture is congruent to a simple strain picture; the *B* letter, stems from Bernoulli, and *D-regions*, where the absence of a simple cinematic behavior involve complex stress picture; in this way there are regions with diffusive stress, by which stems the letter *D*.

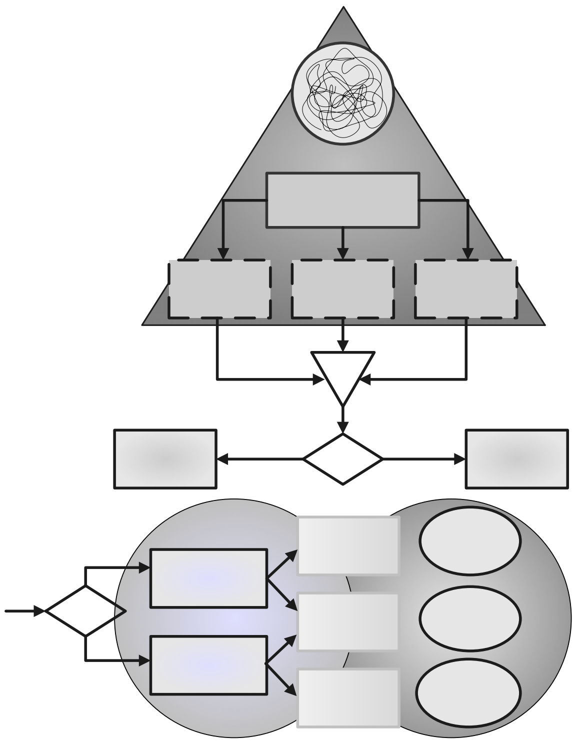


Figure 3. Modeling process from theory to global knowledge to specific practice.

It appears necessary to divide the structural system analysis in several phases, hierarchically organized as:

- Global analysis;
- Local analysis at a first under level;
- Local analysis at a second under level;
- ….

The layout of this multilevel analysis process, can be formalized through the substructuring concept, with the first analysis level executed with numerical models able to gain the global aspect of the structural behavior (for example, with Bernoulli beam elements). It is important to note that (Figure 6):

- All the connections of the structural elements are configured as *D*-regions;
- The global behavior of the structure is the result, from a macroscopic point of view, of the integration of the local behavior of these *D*-regions;
- The local possible crisis, can be dangerous for the integrity (robustness) of the overall structural organism and this must be avoided with an accurate design;
- The local behavior, particularly the local strain, can lead to an unacceptable behavior (for example, regarding the second order effects).

It must be noticed how the complexity of structures such as the Messina Bridge results just from the matching and the interactions peculiar of this system at local behavior: in fact, it is possible the arise of secondary effects to jeopardize the design. The development of these mechanisms in fact, must be identified by the modeling and opportunely dominated in the design strategy (Sgambi & Biondini & Bontempi & Frangopol, 2004).

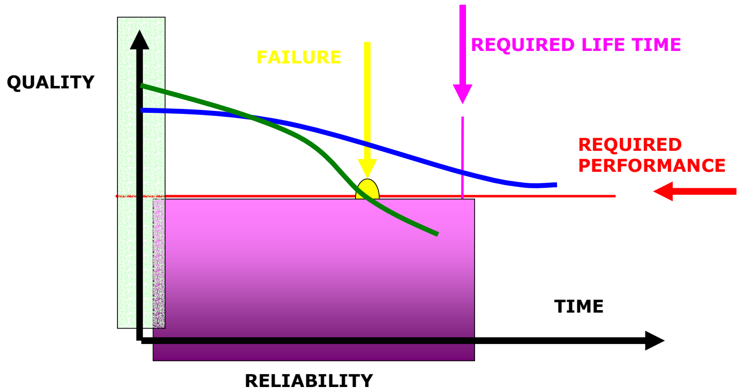


Figure 4. Framework for the performance identification of the structure.

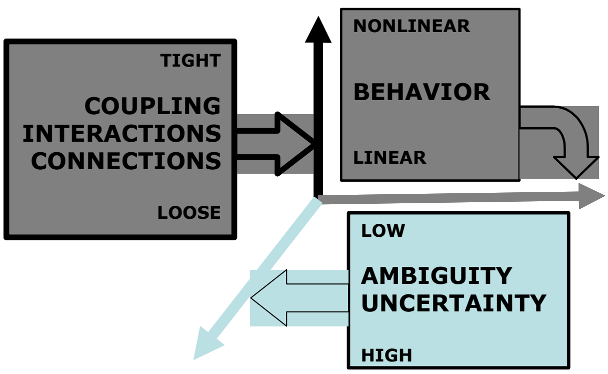


Figure 5. Complexity of the structural behavior as result of nonlinearity, coupling and uncertainty.

2.2 *Exploring the model and handling uncertainties*

For structural systems with non linear behavior a realistic description of the response under all load levels can be obtained only by taking the actual non linearity into account. In this context, thought the reliability of the structure as resulting from a general and comprehensive examination of all its possible failure modes, one must pay attention to the following four aspects which define the assessment process:

- Available data;
- Modeling of the uncertainties;
- Nonlinear structural analysis;
- Synthesis of the results.

On this subject, different approaches have been developed, more of them follow a probabilistic approach. The application of these methods need the definition of the problem in a probabilistic way and require the exact distributions modeling the stochastic random variables involving in the structure. But, sometimes, this is not simple because of the physic of phenomenon studied can be complex and not describing, in a correct form, as a stochastic process. Another limit of more of these approaches is the large number of simulation required to obtain the exact result. As a consequence a high computational effort is needed. With a limited number of simulations just an estimation of the exact result is possible. Some methods to optimize these procedures are proposed in literature.

GRAVITIES OF FAILURES

LEVEL OF FAILURE: INFLUENCES	STRUCTURAL DAMAGE	SERVICE-ABILITY	SAFETY OF THINGS	SAFETY OF PERSONS
MINOR	ON STRUCTURAL COMPONENT	MAY BE	-	-
MAJOR	ON STRUCTURAL ELEMENT	YES	MAY BE	-
SEVERE	ON (LARGE) STRUCTURAL PART	YES	YES	MAY BE
CATA-STROPHIC	ON STRUCTURAL SYSTEM	YES	YES	YES

Figure 6. Gravities of failure for a complex structure like a long span suspension bridge.

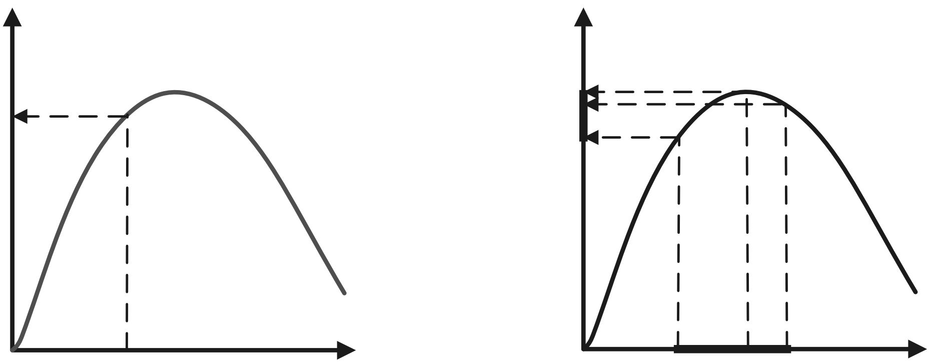
The fuzzy theory is another method to investigate the uncertainties. The fuzzy logic is able to implement in computer code, through formal systems, also linguistic definitions of complex concepts (Petrilli, 2003). This means that every experimental information can be assumed by the method and the problem to be solved concerns with the exploiting of the maximum information from the trials. Therefore, with the adoption of a strategic planning of simulation, the non linear behavior of a structure can be investigate, this taking in account a large number of uncertainties and with a reasonable computational effort.

The fuzzy logic is based on the definition of a membership function describing the parameters of the problem. The membership function represents a set of possible values that the parameter can assume, but not the probable values; therefore, the shape of the function can be chosen on the basis of an expert judgment and not on a probabilistic distribution of the parameter values (Biondini & Bontempi & Malerba, 2000).

Let make an example: let p be a parameter belonging to the set of quantities, which define the structural problem and λ a load multiplier. It is clear that to each set of parameters corresponds a set of limit load multiplier, one of them for each assigned limit state. For sake of simplicity, one starts the considerations by considering the relationship between one single parameter p and one single limit state defined by its corresponding limit load multiplier λ. At first, it is worth noting that, in general, such relationship is non-linear even if the behavior of the system is linear. This is typical of the design process where the structural properties, which correlate loads and displacements are considered as design variables. Thus, the non linear law $\lambda=\lambda(p)$ can be drawn as in Figure 7-a, which shows that for each value of p, there is a corresponding value of λ. However, from Figure 7-b it is also clear that the response interval $[\lambda_{min}; \lambda_{max}]$ corresponding to $[p_{min}; p_{max}]$ cannot be simply obtained from $\lambda(p_{min})$ and $\lambda(p_{max})$. The problem of finding the interval response can be instead properly formulated as an optimization problem by assuming the objective function to be maximized as the size of the response interval itself. Better speaking, the bounding of the structural response interval can be framed as an anti-optimization problem. In particular, for the general case of n independent parameter p, collected in a vector $x=[p_1;$

$p_1; \ldots. p_n]$, and m assigned limit states, the following objective function is introduced:

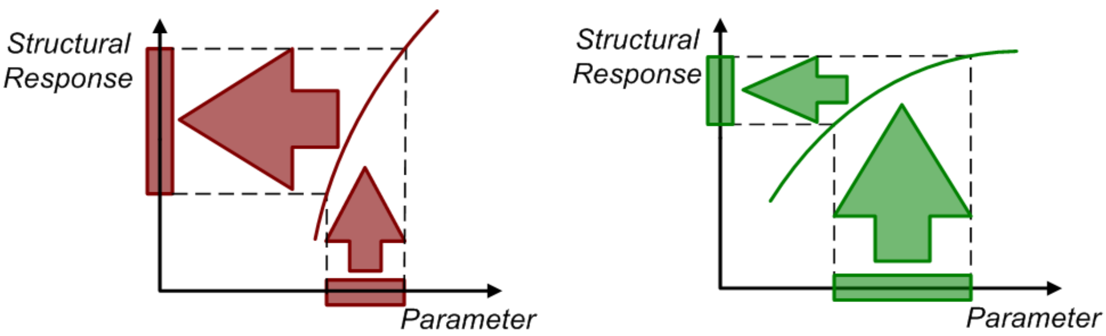
$$F(\mathbf{x}) = \sum_{i=1}^{m} \left(\lambda_{i,\max} - \lambda_{i,\min} \right) \tag{1}$$



(a) (b)

Figure 7. (a) Relationship between a structural parameter p and a limit state load multiplier λ; (b) Interval of the limit state multiplier λ corresponding to an interval of the parameter p.

Moreover, a sensitivity analysis should be conducted in order to investigate the proneness of output results to changes in the input parameters due to uncertainty and/or vagueness, as shown in Figure 8.



(a) (b)

Figure 8. Sensitivity of the structural response: a) a small change in input parameters leads to a large uncertainty in the output results; b) the structural response is not affected by input's vagueness

3 STRUCTURAL ANALYSIS

Static and cinematic parameters have been chosen carefully in order to understand the real behavior of the structure toward the performance condition preliminarily identified as prominent. This complex analysis can be supported by the knowledge of other experiences concerning other bridges already built in other countries. Relating to the long span and to the traffic typology, some of the performances have been analyzed and then adopted after a phase of correction and improvement both during the design and the construction phases.

The functional run ability performances or the skill ness of the bridge to execute safely the correct functions of roadway and railway connection, concern both static and dynamic aspects: they have to be compatibles with the railway and roadway traffic safety. Adequate comfort standards must also be guaranteed.

The roadway traffic conditions are strictly connected to the complex strain path generated by the load combination expected in the exercise phase, varying with the length and with the stresses generated by the roadway and railway traffic. Essentially, they are formed by the transversal slope (sum of the drainage initial slope and the rotation induced), by the vertical curvature radius and by the vertical and horizontal accelerations induced on the deck. Relatively to the railway run ability, the longitudinal slope, the rail torsion and the respective variations must be also added.

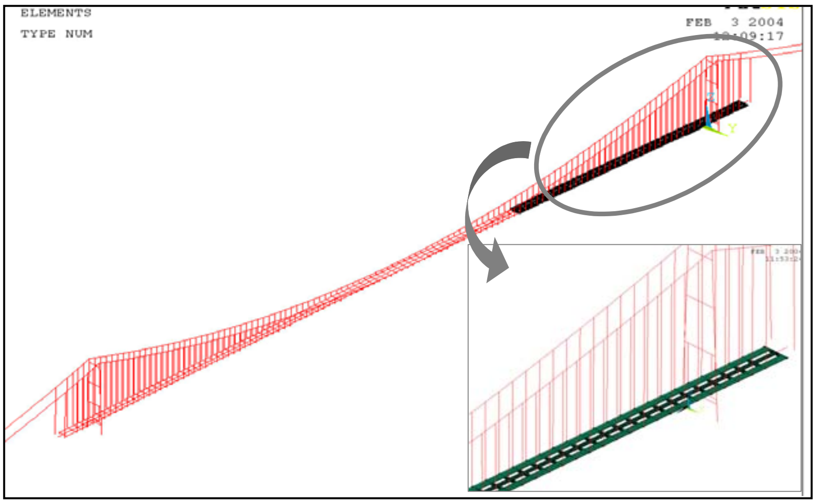


Figure 9. Model of the long span suspension bridge.

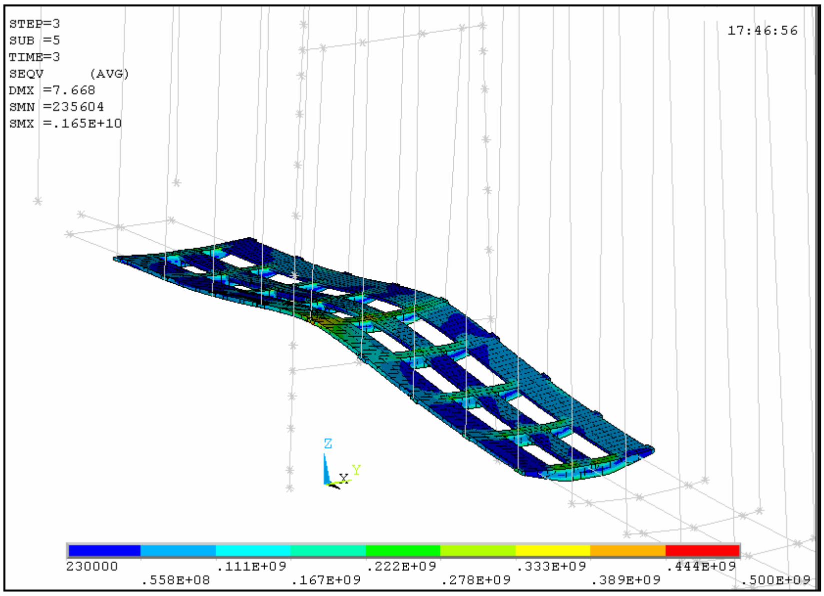


Figure 10. Deformed shape of the bridge and state of stress picture.

Each of these aspects, which influence the run ability, identifies one or more realistic and severe load combinations under which the structure, modeled and calculated with reliable programs, must satisfy the performances attended. Among the actions potentially dangerous toward the run ability, great attention must be paid in analyzing the wind effects, which can really influence the safety and the comfort of the users. Relating to the average economic damage attended by every hour of closure for a year, it's necessary to quantify the Bridges performances with respect to this event, namely the attended number of hours in which the bridge will be closed or open with a series of traffic limitations for the different vehicular categories.

In order to analyze the behavior of the long span suspension bridge, specifically regarding the stress state evaluation, the model of the bridge deck close to the towers (Fig.9) is refined using two-dimensional finite elements working according to the shell theory. This zone, built with special elements, can be considered as a large scale *D*-regions, needing detailed modeling to obtain the realistic description of the behavior of the deck. Figure 10 shows the state of the stress picture in the deck (Catallo & Sgambi & Silvestri, 2003; Catallo & Di Mella & Silvestri, 2003).

4 ACKNOWLEDGEMENTS

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