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A FUZZY APPROACH IN THE SEISMIC ANALYSIS OF LONG SPAN SUSPENSION BRIDGES

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SUMMARY

This study deals with the treatments of uncertainties in the seismic analysis of complex structures. As complex structure, one has considered a long span suspension bridge, whose main span is *3300 m* long. This is, without doubt, a very complex structure for the nonlinearities, uncertainties and interactions involved in its behaviour. This paper focuses the attention on the definition of the seismic input (artificial accelerograms) and the following dynamical analyses which are developed in presence of uncertainties. In particular, one has considered the uncertainties involved in the seismic intensity and in the seismic direction. In order to treat these uncertainties one has developed an analysis based on the fuzzy theory. The procedure performed, in order to reproduce the fuzzy response of the bridge, is illustrated.

INTRODUCTION

The safety of the complex structures, with regards to the seismic events, must be evaluated through various seismic simulations. The seismic simulations have to be planned in order to assure the safety of the structure towards both the service and the ultimate state limits.
With the purpose to improve the robustness of the results and to control the numerous uncertainties and approximations involved in the structural analyses, many analyses with different structural codes and different models should be developed [1]. Different seismic simulations have to be developed to give statistical significance to the analyses.
The nonlinearity involved in the problem must be considered. In particular, in addition to the geometric nonlinearities, the material and contact nonlinearities concerning the nonlinear devices have to be taken into account. In fact, these nonlinearities can influence the local responses of the structure, all around their location, and, therefore, the structural serviceability. This work deals with the evaluation of some response parameters which describe the structural behavior. The displacements near the nonlinear devices will be investigated taking into consideration some uncertainties involved in the seismic input. In fact, one can create several artificial accelerograms to describe the seismic event: however, it will be affected by numerous uncertainties associated with the seismic intensity, the frequency contents and the direction of the seismic event. It is comprehensible that a consistent seismic analysis cannot be performed in a deterministic way but more sophisticated procedures have to be considered. A fuzzy approach to the

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seismic response evaluation it is a very attractive method. In fact, fuzzy sets and fuzzy logic are means for representing, manipulating and utilizing uncertain information. Usually a fuzzy approach is faster than other approaches and it is applicable when the data about the uncertain variables are limited [2]. Because of those two characteristics, the fuzzy approach is a more suitable method to be used in this kind of study. In effect, when one deals with long suspension bridges, the data about the geological condition near the bridge are, often, limited. The geological inspections are expensive and the region interested by the seismic event it is very large. In these conditions, the artificial accelerograms will be affected by great uncertainties. If one considers also the time of the analysis required to reproduce the structural response for every artificial accelerogram, it is clear that the fuzzy approach is a suitable method when compared with other nondeterministic methods.

DESCRIPTION OF THE STRUCTURE

Structural model

The subject of this study is a long suspension bridge with its main span *3300 m* long (see the Figure 1). The total length of the deck, *60 m* wide, is *3666 m* (including side spans). The deck is formed by three box sections, the outer ones for the roadways and the central one for the railway. The roadway deck has three lanes for each carriageway (two driving lanes and one emergency lane), each *3.75 m* wide, while the railway section has two tracks [1], [3].

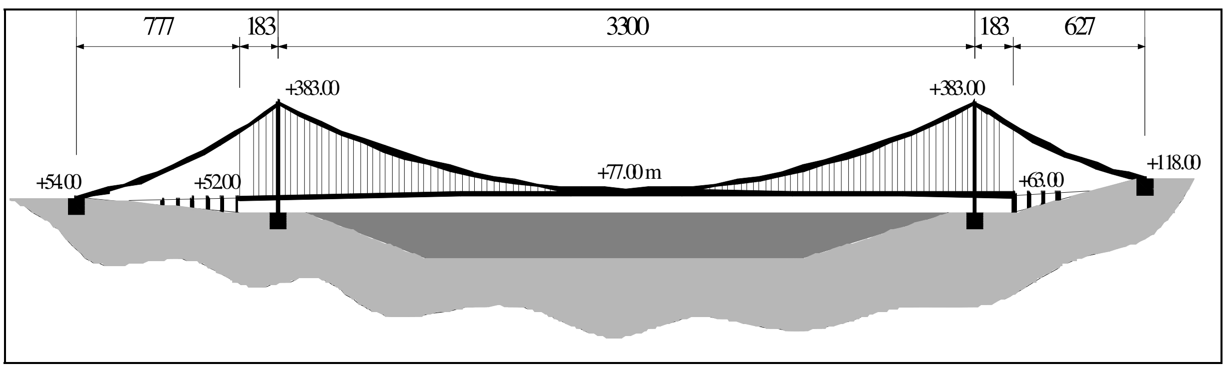

Figure 1: Geometrical representation of the long suspension bridge considered

The two towers are *383 m* high and the deck, in the middle of the bridge, is *77 m* high in order to provide a minimum vertical clearance for navigation of *60 m* – with the most unfavourable static load conditions – over a width of *600 m*. The bridge suspension system relies on two pairs of steel cables, each with a diameter of *1.24 m* and a total length, between the anchor blocks, of *5300 m*.

In the tower zones (points 5 and 8 in Figure 2) nonlinear links are present between the tower and the railway box section both in the transversal and in longitudinal direction. These nonlinear links have a material and a contact nonlinearities because it is present a gap in which the displacement is free. The free displacement for the nonlinear device, is *3* centimetres in transversal direction while it is *50* centimetres along the longitudinal direction.

The numerical model has been developed using 3D beam finite elements, each node having six degrees of freedom [4], [5], [6]. The permanent loads and the masses are modeled as distributed along the elements [1].

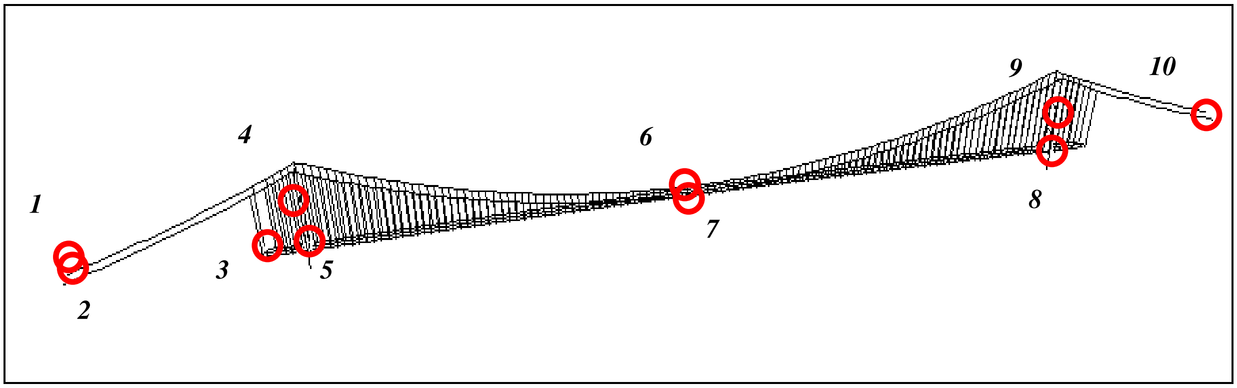

Figure 2: Numerical model and measure points of the long suspension bridge considered

In Figure 2, one points out the measure points where the structural response is analyzed. In particular, one has considered the following parameters:

Measure point	Parameter
1 – TC	Tension in the principal cable
2 – TC	Tension in the principal cable
3 – LD	Longitudinal displacement
4 – TH	Tension in the left side hanging
5 – TD	Transversal displacement
5 – VD	Vertical displacement
6 – TC	Tension in the principal cable
7 – TD	Transversal displacement
7 – VD	Vertical displacement
8 – TD	Transversal displacement
8 – VD	Vertical displacement
9 – TH	Tension in the left side hanging
10 – TC	Tension in the principal cable

Table 1: Measure parameters used

Structural complexity

The complexity of the structural behavior increases if the numerical model has to consider:

- Nonlinearities
- Uncertainties
- Interactions

in order to reproduce the proper behavior of the structure. A long suspension bridge can be rightly defined a complex structure. In fact in its global behavior one can find:

- Nonlinearity: geometrical nonlinearities in cables, material and contact nonlinearities in the nonlinear devices and in the soil behavior.
- Uncertainties: numerical approximations, load definitions, geometrical and material uncertainties.
- Interactions: soil-structure, wind-structure, vehicle-structure and its combinations.

It is very hard to investigate the global response of these kind of structures without consider simplified hypotheses. Certainly, the simplifications have to be chosen in relation with the kind of analysis developed. In this study one has focused the attention on the uncertainties and on the fuzzy response of the bridge: therefore, one has not considered interactions problems.

ARTIFICIAL ACCELEROGRAMS

The seismic input has been modeled using artificial accelerograms. These accelerograms have been create considering a response spectrum based on the soil characteristics of the region interested by the structure. One has made two kind of accelerograms, the first one for the horizontal component of the seismic excitation and the second one for the vertical component. The temporal development of the accelerograms is characterized by three parts. In the first one, one has an increasing intensity of the seismic excitation, the second one is characterized by a constant intensity while in the third one has a decreasing intensity. The length of these parts is random, and the total length of the seismic excitation is about *50 - 60 seconds*.

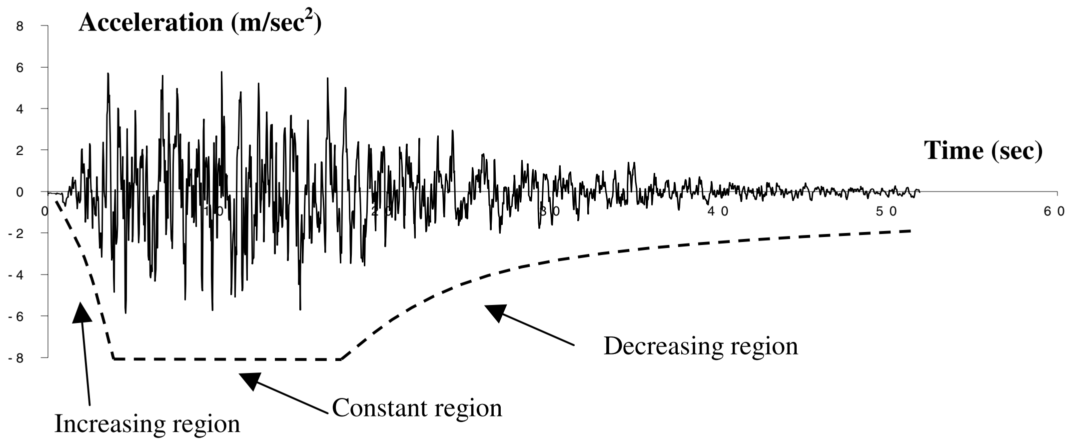

Figure 3: Artificial accelerogram numerically generated

The Peak Ground Accelerations (PGA) along the vertical, longitudinal and transversal axis are fixed as:

Axis direction	Acceleration ratio (PGA/g)	PGA (m/sec^2)
Vertical	*0.45*	*4.41*
Transversal	*0.60*	*5.88*
Longitudinal	*0.48*	*4.71*

Table 2: Peak acceleration along the three Cartesian directions

In order to have a random principal acceleration during the seismic event, the seismic input is assembled using different accelerogram history along each Cartesian axis. In this way the excitation directions change *"randomly"* during the seismic event.

NONLINEAR FUZZY APPROACH

Nonlinear behavior

The behavior of the model considered is, certainly, a nonlinear one. The nonlinearities come from the cables behavior and the nonlinear links which reproduce the connection between the tower and the railway box section. One can assess the importance of the nonlinear behavior analyzing the model under a seismic action with PGA = *K* and the same model with PGA = *1*. If the behavior is linear the superimposition of the effects will be applicable. In this case both the response of the analysis with PGA = *1*, multiplied for the *K* value, and the response of the analysis with PGA = *K* must give the same results.

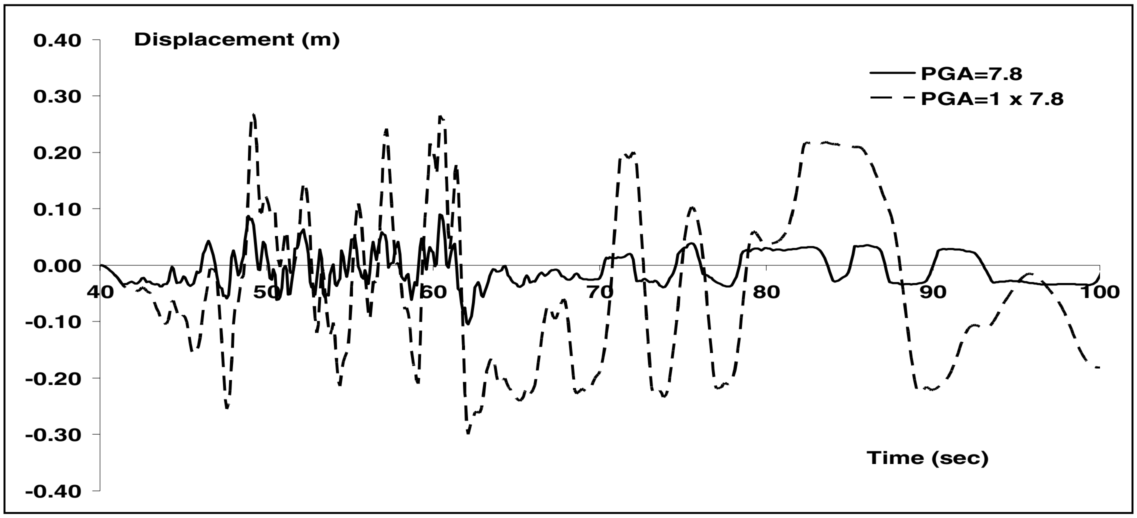

Figure 4: Effect of the nonlinearities (*K = 7.8*)

For brevity, one has reported, in Figure 4, only the response in the *5 – TD* measure point. As one can observe from the Figure 4, the superimposition of the effect fails. In this structure, the nonlinear effect is very important and can influence the uncertainties sensibility of the model. Therefore the fuzzy analysis must consider carefully the nonlinear behavior.

Fuzzy approach

In order to represent and investigate the uncertainties importance both for the seismic intensity and the seismic direction, one develops a fuzzy approach to the seismic event. Fuzzy sets and fuzzy logic are, in fact, means for representing, manipulating and utilizing uncertain information. In particular, one has to give an estimation of one or more output parameters (displacements, accelerations, tensions…) considering one or more uncertain input parameters (seismic intensity, material properties…).

An uncertain input parameter can be fuzzified using a triangular (or another shape) membership function. There are various types of membership functions which are commonly used in fuzzy theory. The choice of the shape depends on the specific application. In this paper one has utilized a Λ – function (triangle shape). One can assign to this function the label: "*input membership function*". The output parameter is linked to the input parameter by the structural behavior. In general there will exist a nonlinear relation between the input parameters and the output parameters. One can assign to this relation the label: "*translation function*". In fact, one can use this function to reproduce the uncertainties on the output variables. Sectioning the input membership functions for specified degree values of the membership function and using the outputs of the translation function, it is possible to transform the input interval in the output interval (Figure 4). The "*output membership function*" is built repeating this procedure for different values of the input membership function (different μ values) [2], [7], [8].

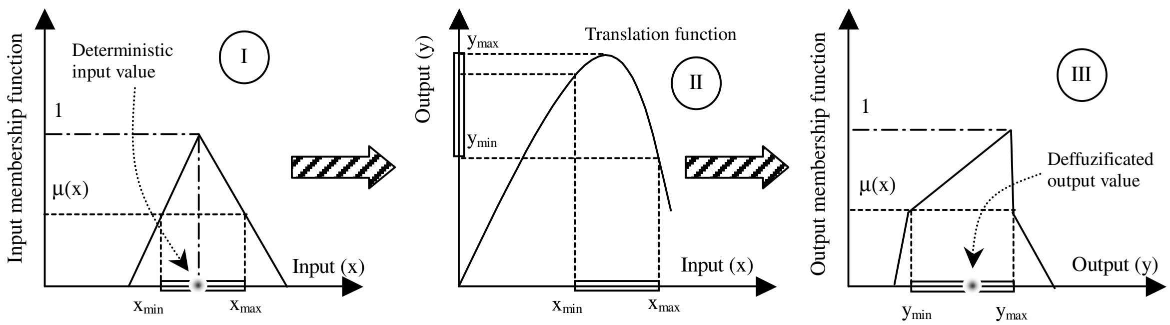

Figure 4: Estimate of the output interval from the input interval

When one has built the output membership function, it is necessary to produce a crisp value to represent the distributed state of the output. The mathematical procedure employed to convert the fuzzy values into crisp values is know as "*defuzzification procedure*". In literature, various defuzzification methods have been suggested. Different methods provide similar results (but not the same results) for an identical input data. The choice of the proper defuzzification methods depends on the applications. In this work, one has assumed a center of gravity method as a defuzzification procedure.

$$\tilde{x} = \frac{\int \mu(x) \cdot x \cdot dx}{\int \mu(x) \cdot dx} \qquad (1)$$

In this study one considers as uncertain the intensity exposed in Table 2. The uncertain range considered is assumed equal to 30% along each Cartesian direction. Therefore one can define the following "*cube of intensities*":

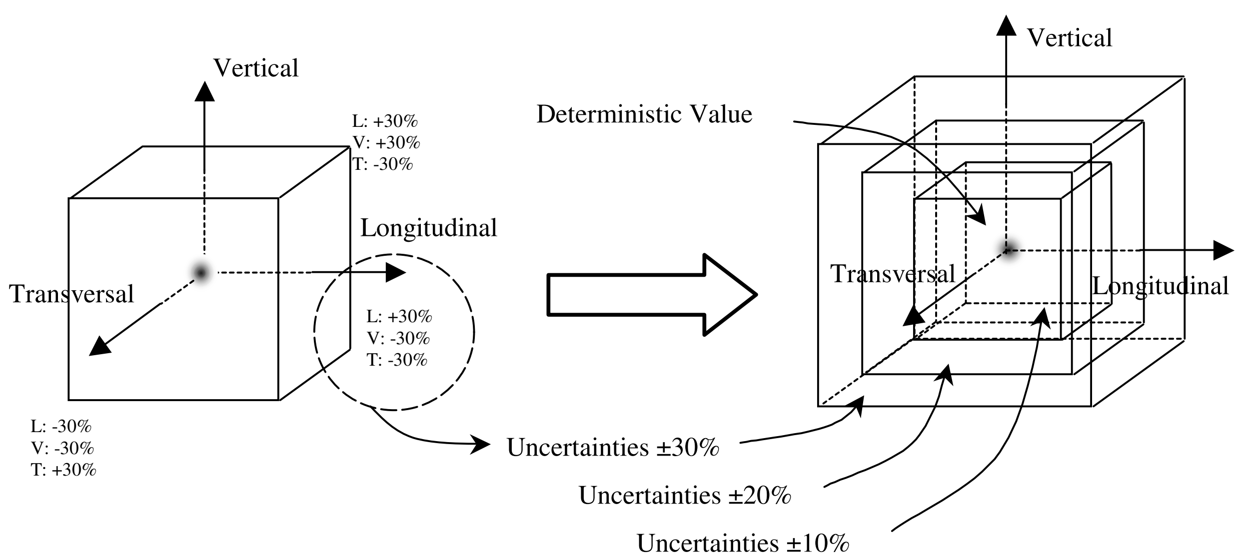

Figure 5: Fuzzification of the seismic intensity. On the left the maximum value of the uncertainties considered, on the right the discretization of the uncertainties interval

In the case developed, one has assumed a triangular input membership function with a membership value equal to one for the deterministic analysis. The membership values associated to different discretizations of the input uncertainties interval (Figure 5) are summarized in the following table:

Membership values	Uncertainties associated
1.00	± *0%* (deterministic value)
0.67	± *10%*
0.33	± *20%*
0.00	± *30%*

Table 3: Membership values of the input membership function

The shape of the input membership function is similar to the Figure 4, but it has four dimensions. In fact, it links three independent variables (the variations of the seismic intensity) with its membership value. In order to build the output membership function, *343* seismic evaluation with different seismic intensity are needed (using the discretization shown on the right of Figure 5 and in Table 3). For the structural calculations one has utilized a commercial code in batch mode, driven by a computer program to govern the seismic analyses (Figure 6). In [1], a discussion about the robustness of the seismic analyses and a critical evaluation of the results are reported.

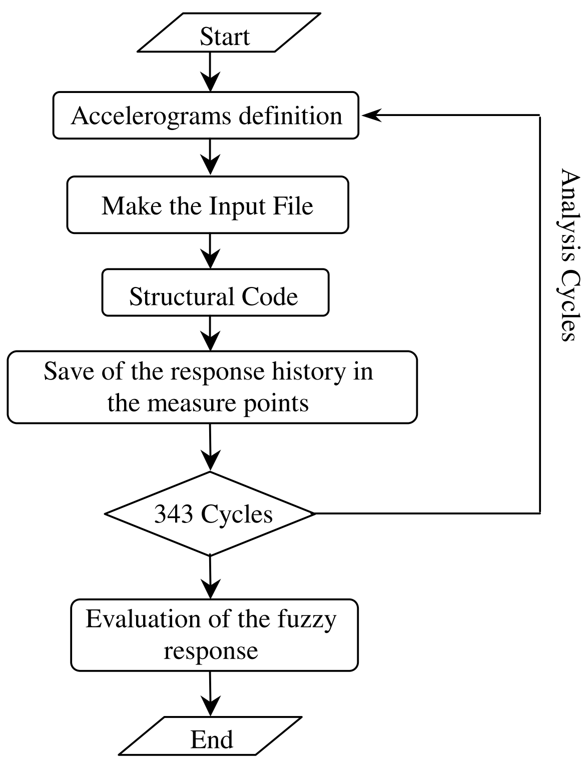

Figure 6: Flow-chart of the program implemented

CONSTRUCTION OF THE FUZZY RESPONSE

In Figure 7, an example of response curves is plotted. These curves represent the transversal displacement of the measure point *5 – TD* during the *343* seismic simulations.

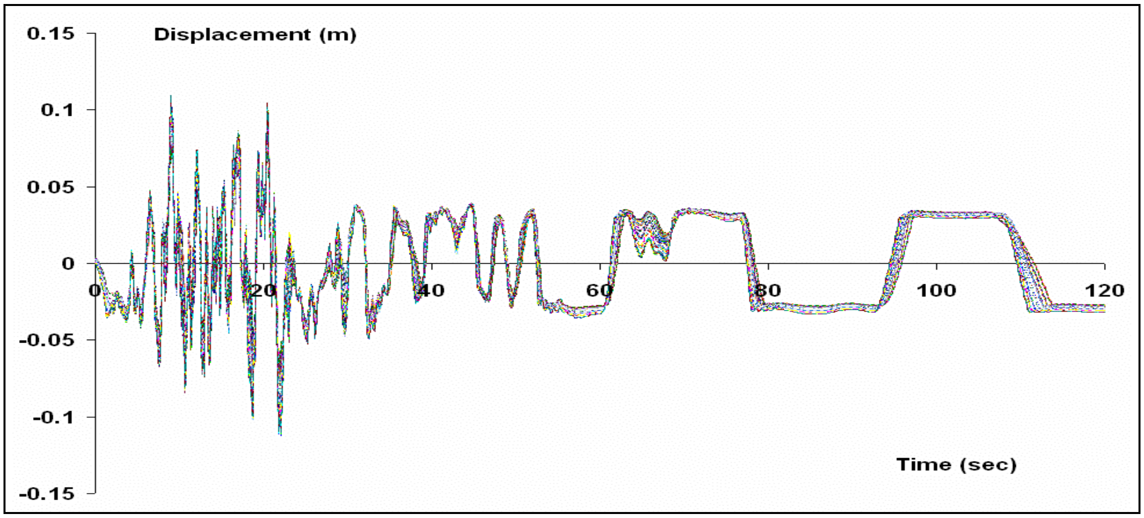

Figure 7: Group of the seismic responses

This particular displacement is influenced by the presence and the characteristics of the nonlinear devices which linked the railway box section with the tower. Observing this figure, it is possible to point out that during the first part of the seismic event (*0 – 30 seconds*) this device is not working; in fact the maximum transversal displacement is about *10 centimeters* versus the *3 centimeters* of free displacement permitted by the device. In the second part of the seismic event, the effect of the non linear device is evident. It is possible to put in evidence the area in which the seismic response is present, drawing an envelope diagram for the curves considered.

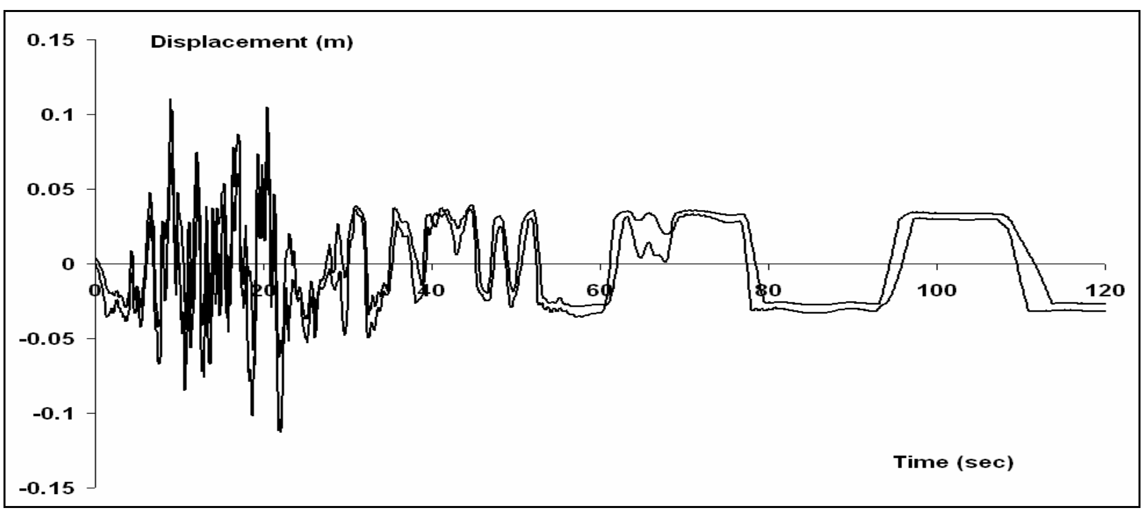

Figure 8: Envelope diagram for the transversal displacement in the point of measure *5 – TD*

Each seismic response evaluated is naturally included between the two curves represented in the envelop diagrams, nevertheless the fuzzy response must be included into the envelop diagram.

At each output time, it is possible to use the fuzzy theory in order to build the fuzzified response. This is represented, at each output time, by a distorted triangle which assigns a specified uncertain function to every zone included into the envelope diagram.

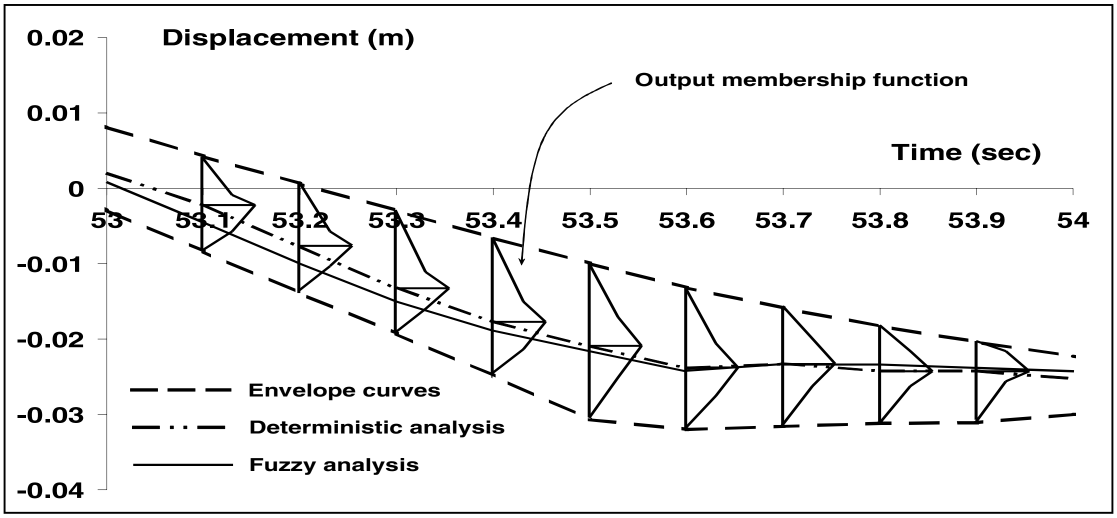

Figure 9: Qualitative image of the fuzzy response construction

Using the defuzzification procedure described in the first part of the work, it is possible to evaluate the fuzzy displacement at each output time and, consequently, the fuzzy response. Obviously, the fuzzy response lies between the two curves of the response envelop but its position depends on the problem nonlinearities. If the problem is linear, the triangles present in the Figure 9 are regulars, because the translation function does not induce distortions in the output membership function. Therefore, the fuzzy response and the deterministic response are identical and one has a "*proportional*" uncertainties sensibility of the structure. Of course, the fuzzy response is located between the two envelope curves (Figure 10) but if the nonlinearities are relevant, the output membership function presents a distorted shape and the position of the fuzzy response is estimated by a defuzzification procedure.

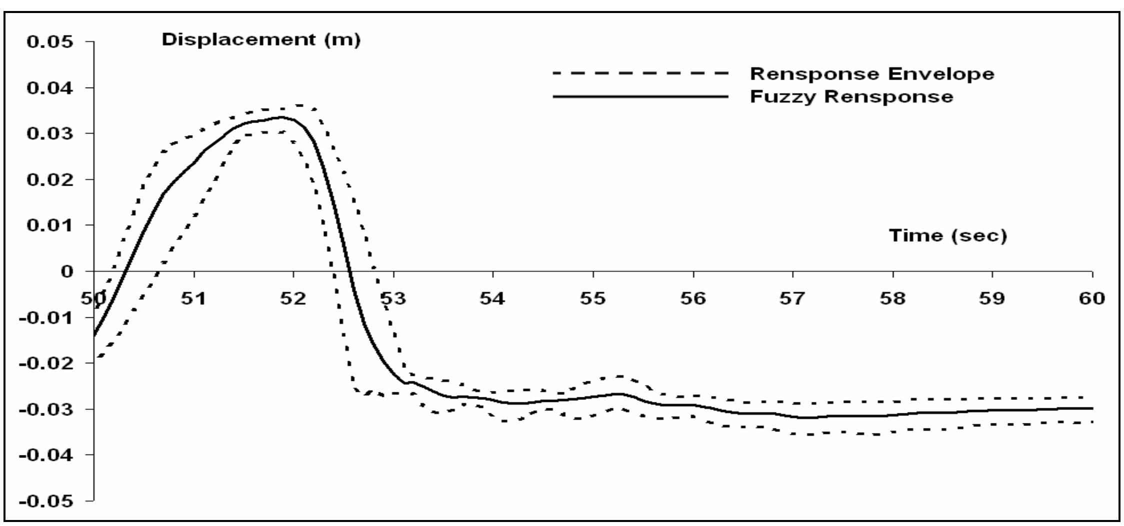

Figure 10: Comparison between the fuzzy response and the response envelope

The fuzzy response has to be evaluated for every output parameter which characterizes the structural behaviour. Some of these output curves are reported in this page.

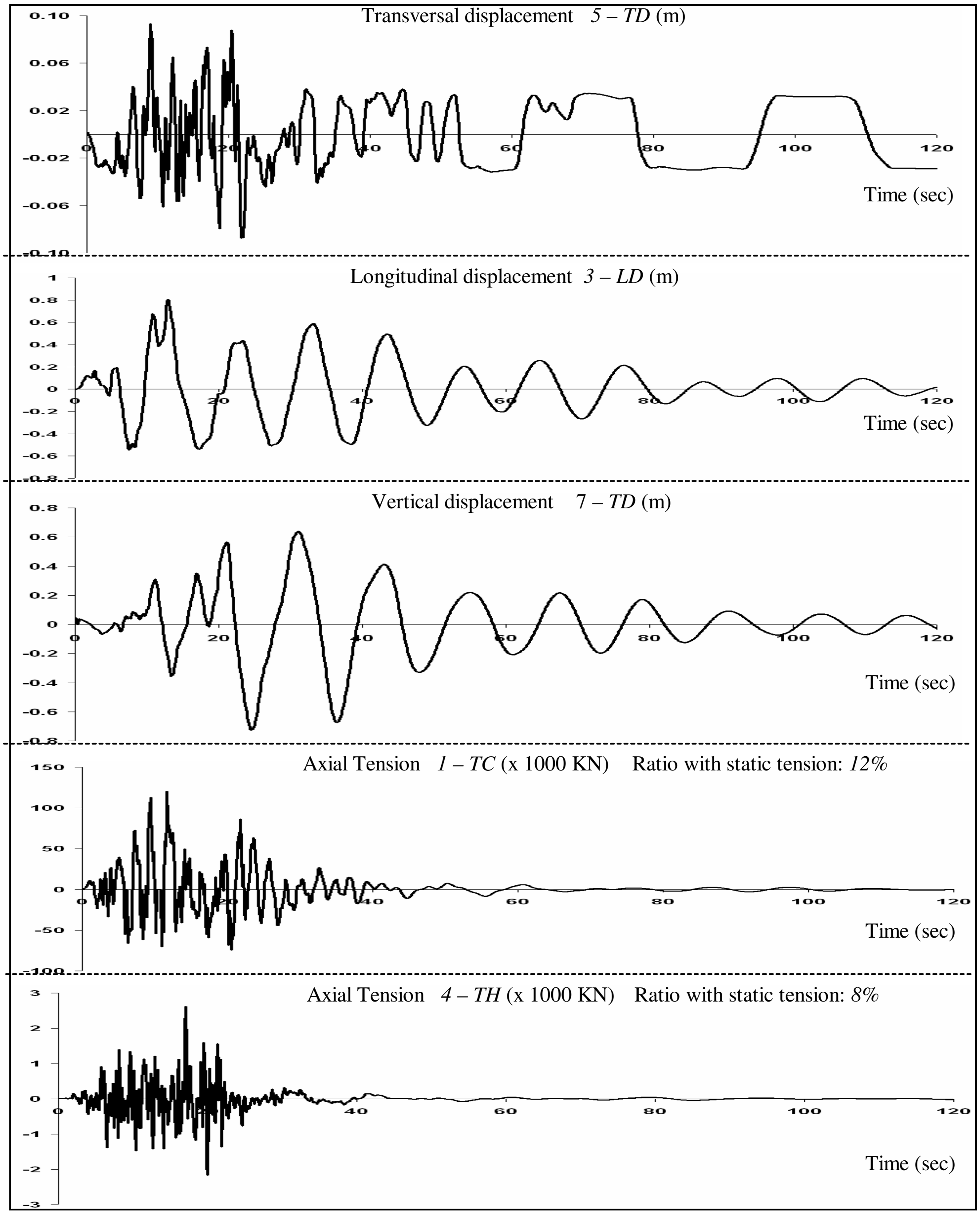

Figure 11: Some fuzzy responses evaluated on the measure points of Figure 2

For the sake of brevity, one has reported in Figure 11 only five fuzzy response curves. In Table 4, one has summarized the results of the fuzzy analysis. The maximum value and the minimum value of the parameters, indicated in Table 1, are shown.

Measure point	Parameter	Maximum	Minimum
1 – TC	Tension in the principal cable	120.2	-77.08
2 – TC	Tension in the principal cable	119.9	-74.50
3 – LD	Longitudinal displacement	0.81	-0.55
4 – TH	Tension in the left side hanging	21.32	-17.12
5 – TD	Transversal displacement	0.081	-0.084
5 – VD	Vertical displacement	0.053	-0.060
6 – TC	Tension in the principal cable	38.15	-39.44
7 – TD	Transversal displacement	0.64	-0.72
7 – VD	Vertical displacement	0.62	-0.69
8 – TD	Transversal displacement	0.093	-0.098
8 – VD	Vertical displacement	0.065	-0.072
9 – TH	Tension in the left side hanging	26.2	-21.6
10 – TC	Tension in the principal cable	119.3	-73.02

Table 4: Variation interval in the fuzzy response curves (displacements = *m*, forces = *KN*)

In Figure 12, a deterministic response and a fuzzy response are plotted for the case studied. One has plotted only the part of the response between *55* and *65 seconds* in order to improve the understanding of the figure. As one can observe, the fuzzy response is, in general, similar to the deterministic response. However, the fuzzy response is a more reliable analysis and it is a suitable analysis in order to evaluate the importance of the uncertainties involved in the problem.

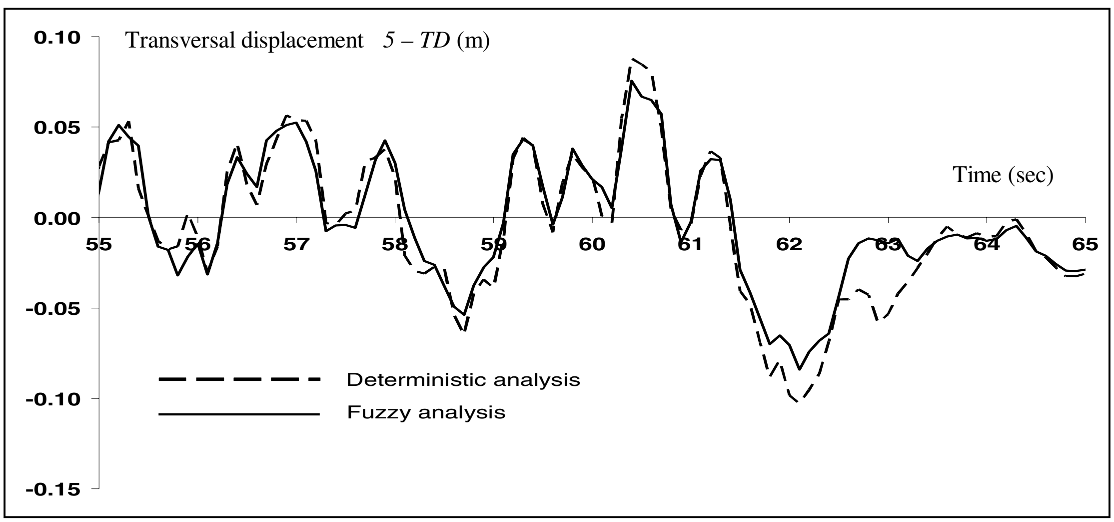

Figure 12: Some fuzzy responses evaluated on the measure point of Figure 2

CONCLUSIONS

In the seismic analyses of complex structures, one cannot forget that the model is affected by uncertainties. These uncertainties can influence the structural behavior and invalidate the analysis outcomes. The complex structure considered in this study is a long suspension bridge. In the model, the geometrical, material and contact nonlinearities are considered to reproduce a structural behavior. In order to estimate the uncertainties importance on the seismic input definition, many analyses have been developed. Using a fuzzy theory, a nonlinear-fuzzy response of the bridge has been built. The fuzzy analysis has a particular significance near the zone where the nonlinear behavior is heavy. In fact, as shown in the text, near these zones the output membership functions are distorted by the nonlinear behavior. The significance of this distortion is a "*non-proportional*" uncertainties sensibility of the structure. It is evident that in these cases, many analyses have to be developed to evaluate the uncertainties importance.

AKNOWLEDGEMENTS

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