Analysis and optimization of a *Safety Line* under dynamic loads

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Abstract

In the construction and maintenance of civil and industrial buildings there is an high risk for the worker to fall from high places. The worker has to be protect with a proper fall protection device able to prevent the human damage but, at the same time, which permits all the movements of the worker. Very effective protection systems are the *Safety Lines*. These systems are based on the positioning of fixed cables to which the user can be connected with a moving cable.

In this way the safety of the worker is assured if the cables systems are dimensioned to resist to the worker weight increased by the dynamical effect, with a proper safety coefficient. However, the cable systems have a structural behaviour with a very low damping and the oscillations of the attached mass can be very large. Clearly, these systems have to arrest the fall minimizing the pendulum effect, therefore one or more dissipative devices have to be installed.

In this paper a *Safety Line* installed by the Italian Society "Nuovo Modulo S.p.A." (BG) on its new buildings is investigated with the intention to show the importance of a proper design of the dissipation devices. Using a finite element program the authors investigated the dynamical behaviour of the installed safety system. The design of the mechanical properties of the dissipation devices was performed using a genetic algorithms approach.

Keywords: passive control, genetic algorithms, optimization, safety, dynamical analysis

1 Introduction

Since *1997*, in Italy, it has been obligatory to install safety systems conform to the UNI - EN 795 Standard – "Protection against falls from a height" [1]. The people who work in hazardous area or work at a height have to work in safety.

For example, a useful fall protection can be performed with a proper positioning of a *Safety Line* system. This system consists in one or more fixed cables to which the worker can be connected with a moving cable. It is clear that the *Safety Line* system is composed by the cables, the supports, the anchorages and the dissipative devices.

It is very important the presence of the dissipative devices in order to reduce the axial force on the cable during the possible fall of a body. This paper analyzes the dynamic response of a *Safety Line* installed by the Italian Society "Nuovo Modulo S.p.A." [2] on its new building. Purpose of these investigations is to put in evidence with numerical simulation on an actual case, the importance of a proper design of the dissipation device.

Figure 1 shows a simple geometrical survey of the building and the position of the *Safety Line*: *66.6 m* of cables, *4* lateral supports, *2* angular supports and *2* anchorages. The following figures show some particulars of the *Safety Line* considered. In particular, Figure 2 shows the lateral supports of the cable, Figure 3 shows the angle supports and Figure 4 shows the anchorage mechanisms.

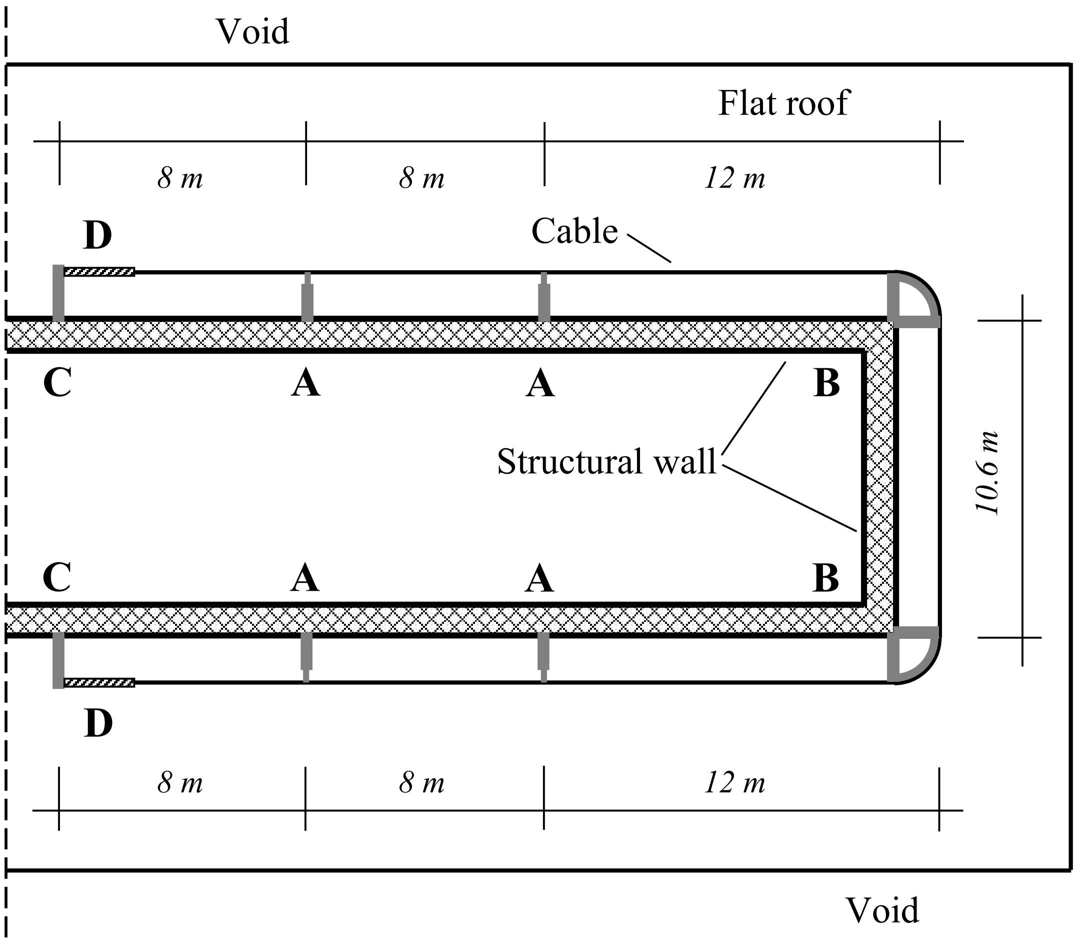

Figure 1: Geometrical survey of the *Safety Line* (A = lateral support, B = angular support, C = Anchorage support, D = dissipative device).

Figure 2: Lateral support of the *Safety Line* (Point A in Figure 1).

Figure 3: Angle support of the *Safety Line* (Point B in Figure 1).

These particulars are evidenced in Figure 1, with the letters A, B, C respectively. In the point D the cable can be anchored to the wall by a passive dissipation device. The proper design of these devices is the final purpose of this study.

It is clearly that the principal function of the lateral support is to limit the sag of the cable (especially when it is loaded by a dynamic load) while the angle supports are necessary to follow the irregularity of the building.

Figure 4 shows the most important point of the *Safety Line*: the anchorage point. One can note that the *Safety Line* is anchored directly to the reinforced concrete wall by a strong collant. In this way, the anchorage zone is very stiff. Figure 4 shows also the pre-tension device used to give a little pre-tension to the cable. Between the pre-tension device and the anchorage support it is possible to insert a dissipative device to control the possible dynamic effects (oscillations of the cable and axial force on the anchorage). The study developed is aimed to show the importance of a proper design of this device. In the following, the authors will assume that this device is the only dissipation mechanism present in the *Safety Line* system. Its importance will be put in evidence through comparisons of the system responses with and without the dissipative device.

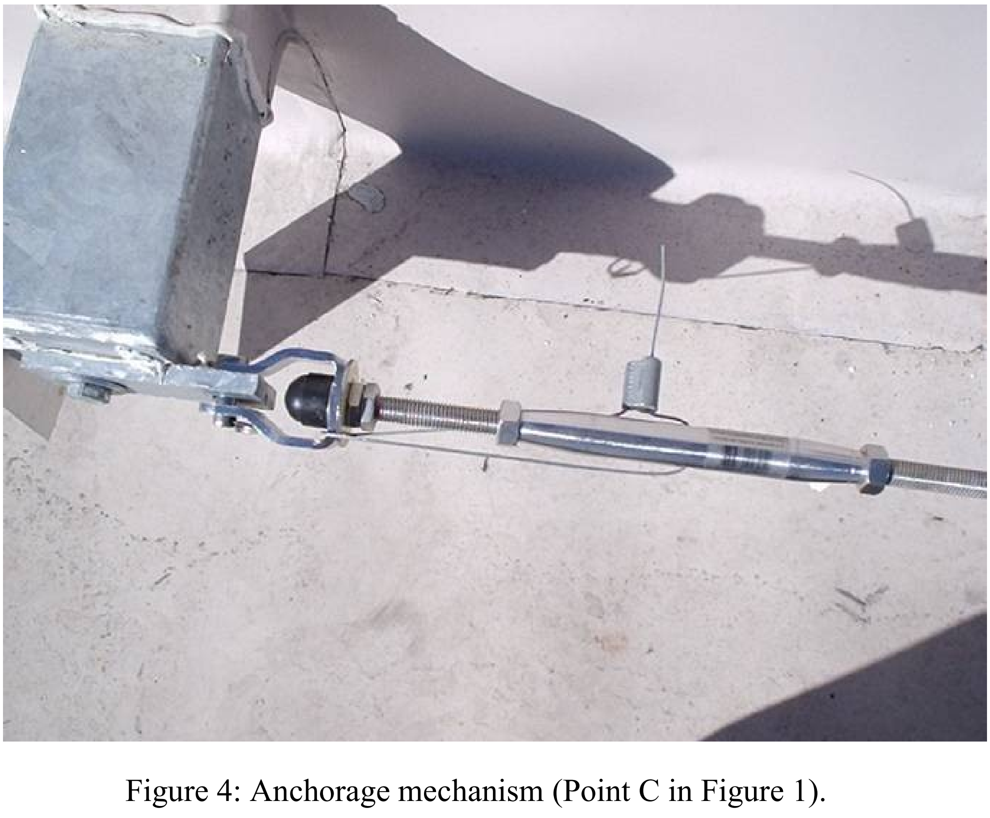

Figure 4: Anchorage mechanism (Point C in Figure 1).

As a dissipative mechanism, the authors will consider an elasto-plastic device in which the energy is dissipated by plastic deformations of the device. A proper design of this device will be developed using a genetic algorithm approach [3, 4] to optimize the mechanical characteristics of the device under dynamic loads.

2 Numerical model of the *Safety Line* system

As emphasized in the previous paragraph, the most delicate and important point of the whole *Safety Line*, is the terminal dissipative device. Its role is to control the dynamic effects caused by the falling body.

An appropriate numerical model [5] is necessary to investigate the effect of the falling body on the structural system. In particular, the global dynamic response of the cable and the localized effects on the anchorage have to be investigated. The analysis and the optimization of the structural system were performed in two steps. At first, the dynamic response of the system without dissipative devices was investigated, while, in a second phase, an optimization of the dissipative devices was performed. The first phase is really important to understand the central role of the dissipative device in this structural system.

The dynamic simulation was performed developing a numerical model with the structural code ADINA [6]. The cable was discretized using truss finite elements in total Lagrangian formulation (large displacements and large strain).

The geometry and the characteristics of the real structure have been simplified [7, 8] adopting some hypotheses to control the lack of information regarding the single parts of the structure (the proper behaviour of the supports, the exact cable geometry, etc.). Figure 5 shows the numerical model used in this study. In particular, one has assumed the following three hypotheses:

1) The structure can be modelled in planar a way, using a series of truss elements placed along the horizontal direction. A planar model is suitable to simplify the geometrical problem and it is legitimated by the continuity of the cable and by the prevalence of the axial stiffness over others resistant mechanisms.

2) The lateral and the angle supports are assumed to be rigid. Only the axial displacement of the cable is permitted in these points and any friction force is assumed between the cable and the supports.

3) The falling body can move itself only along the vertical direction and the action of the falling body is immediately transmitted to the safety cable.

The numerical model shown in Figure 5 was developed considering these hypotheses. The points B in the figure represent the supports of the cable (lateral and angle support) while the letters D indicate the two anchorage mechanism present at the extreme points of the cable. To simulate the presence of dissipative devices close to the anchorage an elasto-plastic truss is inserted between the anchorage and the cable. At last, the letters C indicate the falling body.

As shown in Figure 1, the span length of the cable are *8 – 8 – 12 – 10.6 – 12 – 8 – 8 m*, for a total length of the cable of *66.6 m*. The diameter of the cable is *8 mm* and one has assumed a density of *7980* kg/m^3 and a Young modulus of *198000* N/mm^2. The little pre-tensioning force of *100 N* present in the cable is modelled using an initial strain of *9.95E-6*.

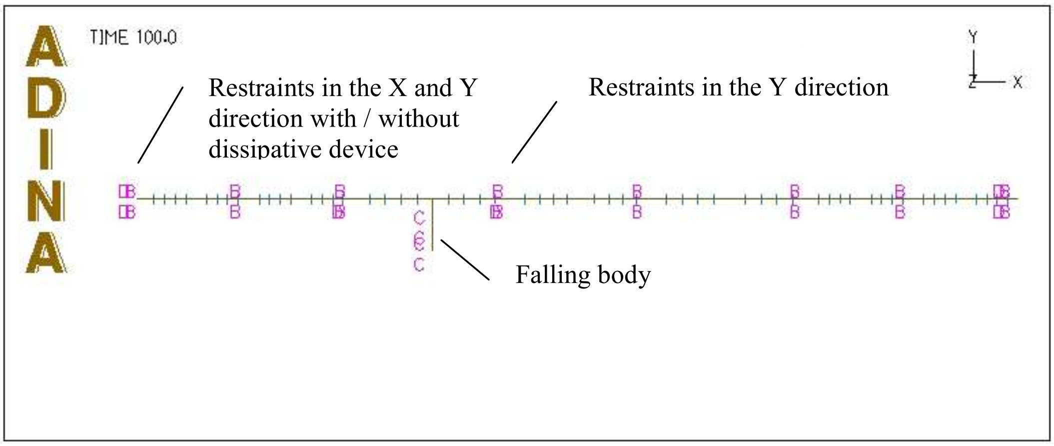

Figure 5: Numerical model developed using ADINA software.

The structural damping is introduced in the model using the Rayleigh formulation. Two Rayleigh parameters are considered, α and β, and the values assigned to them are:

$\alpha = 0.02143$

$\beta = 0.00007143$

These values are esteemed considering a structural damping ratio of 2‰ on the first six deformed shapes of the structure.

Figure 6 shows the two time histories implemented in the numerical model. The dynamical analysis lasts *100 sec*: the first time history (S1) is associated to the application of the gravitational field and the pre-tension of the cable, while the second time history (S2) is associated to the application of the falling body. The falling body appears after *30 sec* and its apparition is simulated in ADINA using "birth and death" elements. When the simulation time reaches the 30^{th} second the elements indicated with the letter C in the Figure 5 appear in the model. Since these elements have a total mass of *100 kg* and there is a gravitational field in the vertical direction, the cable results loaded from a falling mass.

These time histories are represented in Figure 6. This figure can be divided in three zones: A, B and C. In the phase A one has the application of the gravitational field to the structure. In order to limit the numerical oscillations of the cable, the gravitational field is assigned using a linear way during the first *10 sec* of the analysis.

In the phase B any new load is applied to the structure. In this way it is possible to check the amplitude of the numerical oscillation due to the loads applied in the previous phase.

The dynamic simulation of the falling body starts with the phase C. A mass of *100 kg*, jointed to the cable, appears suddenly in the gravitational field, simulating a worker's fall. The phase C lasts *70 sec* in which the dynamic behaviour of the system (cable and mass) is monitored.

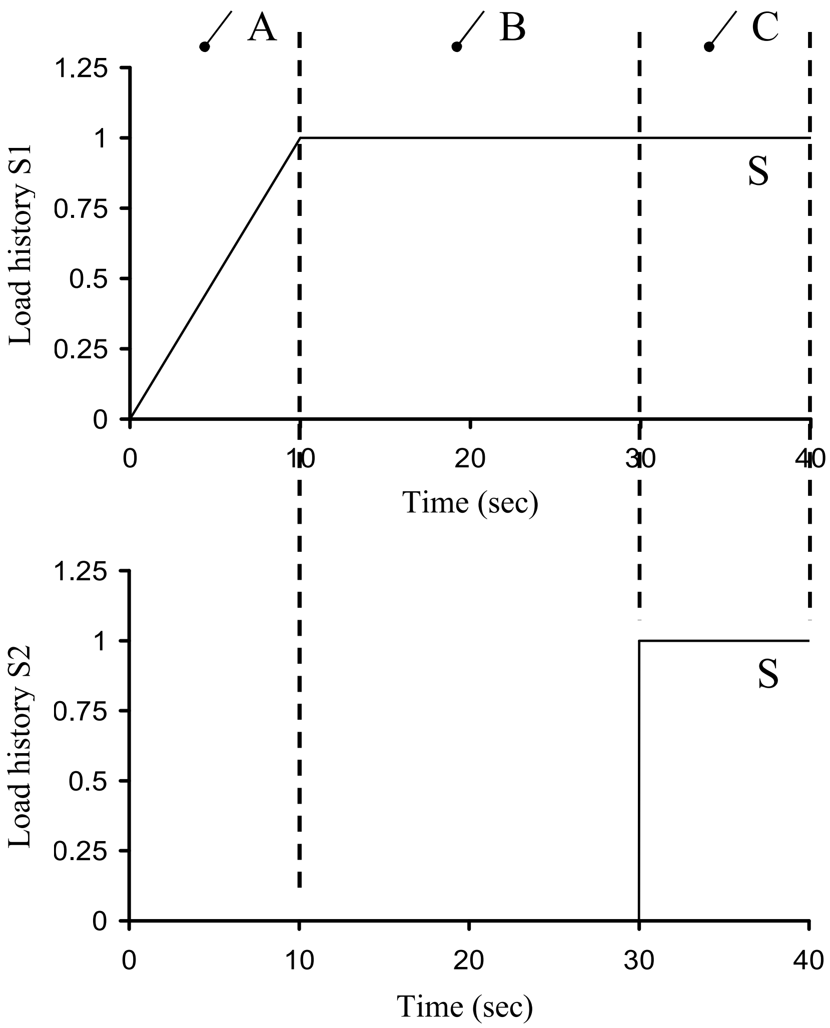

Figure 6: Load history applied to the structure.

The dynamical analysis was performed using the implicit integration method of Newmark with coefficients $\alpha = 0.25$ and $\delta = 0.50$. The next paragraph reports the results of the dynamic analysis in term of modal analysis and time history curves. A proper time step for saving the results was chosen to avoid the aliasing effect on the response curves.

3 Dynamic analyses with a falling body

Although the dynamic analysis was performed using a step by step integration method, a preliminary modal analysis is always suitable to understand the behavior of the structural system [9]. Figure 7 shows the first three shapes vibration modes of the cable-mass system. Clearly, the first shape mode involves strongly the concentrated mass while the following modes excite others parts of the structural system. The first period, indicated in Figure 7, is about *0.81 sec*. while the second period is about *0.19 sec*.

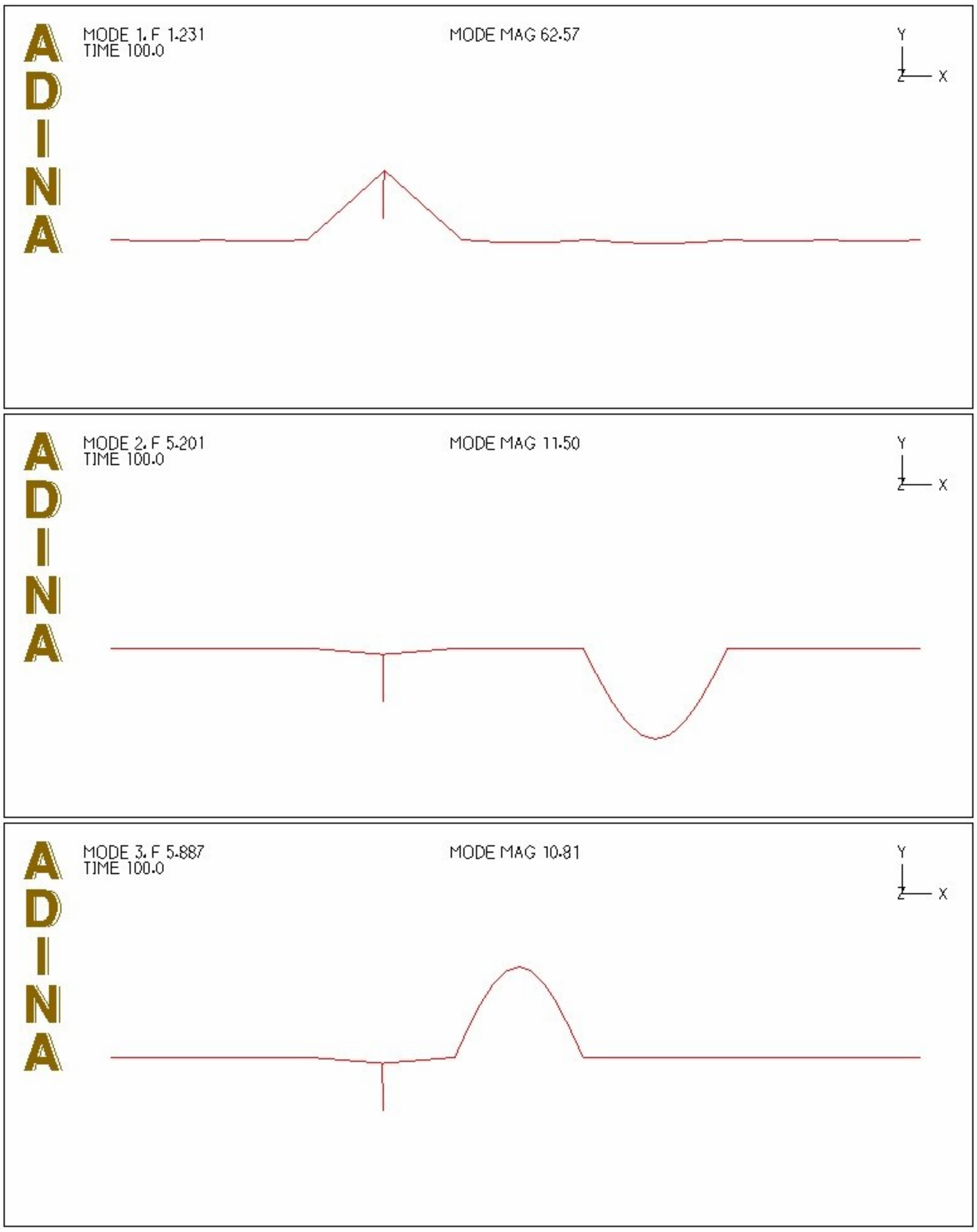

Figure 7: The first three vibration shapes of the cable-mass system.

In order to understand the importance of the dissipative device, the dynamic response was analyzed on two structural systems: the first without dissipative device at the anchorage and the second with an optimized dissipative device.

Figure 8 reports the time histories of the mass displacement and of the axial force at the anchorage for the not controlled system. Since the dissipation of the system is very low, the response is very similar to a not dissipative system. From the graphs shown in Figure 8 it is possible to note that the response is strongly governed by the first mode (the frequency of the oscillation is very close to the frequency of the first oscillation mode). One can also note that the oscillations present in the first part of the time history (*0 – 30 sec*) are small and, presumably, they do not influence the following response (*30 – 100 sec*).

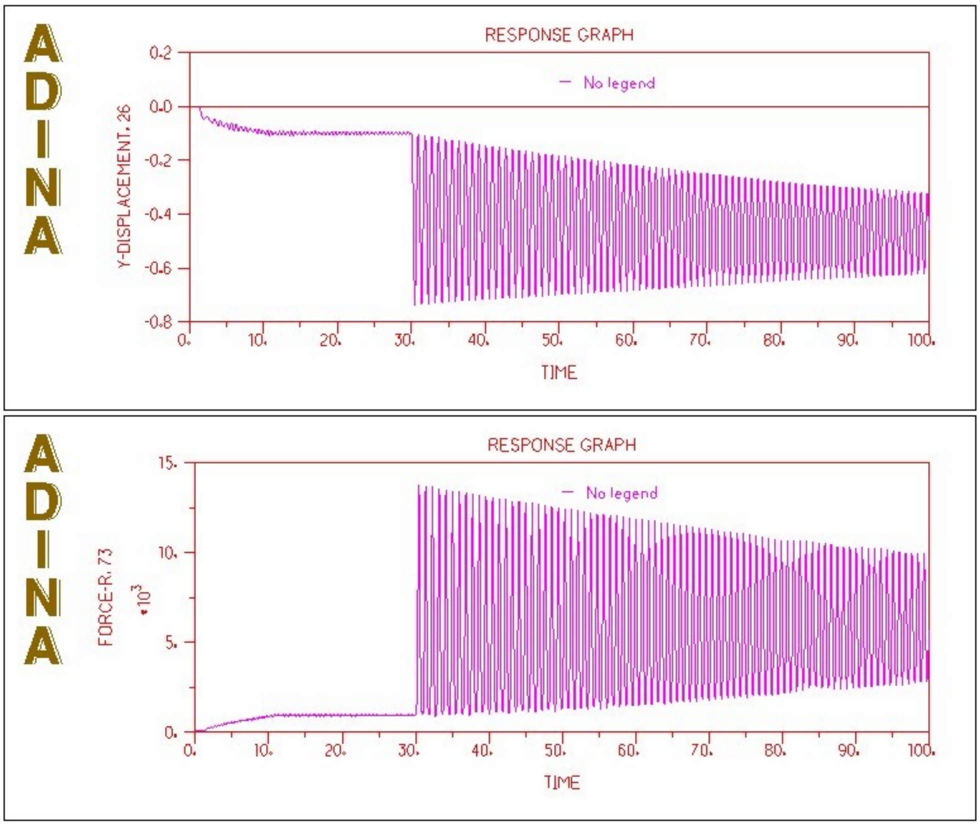

Figure 8: Time histories of mass displacement and anchorage force (not controlled system).

To control the displacement oscillation and to limit the dynamic effect on the anchorage force, a dissipative device can be inserted between the cable and the anchorage. The purpose of the next study is to define the most suitable mechanical properties of the dissipative device. To get this optimized solution, a genetic algorithm approach can be performed.

Genetic algorithms are heuristic algorithms of searching, inspired by Darwin's theory of evolution. Each state of the system (individual) is represented by a string of encoded variables, known as chromosome or genome. During the genetic analysis, different chromosomes are combined or mutated to get new individuals. Using an opportune fitness function, the genetic analysis will select the most suitable individual. This individual will represent the optimized solution of the problem [10, 11]. Important applications performed using this approach are present in the technical literature [12, 13, 14].

Operatively, to perform a genetic analysis can be used the same procedure described in [11, 15]. It is possible to use a genetic algorithm coupled with a commercial code like ADINA [6]: the genetic algorithm drives the analysis while ADINA performs the structural analyses. Figure 9 represents the flow-chart of the genetic algorithm implemented.

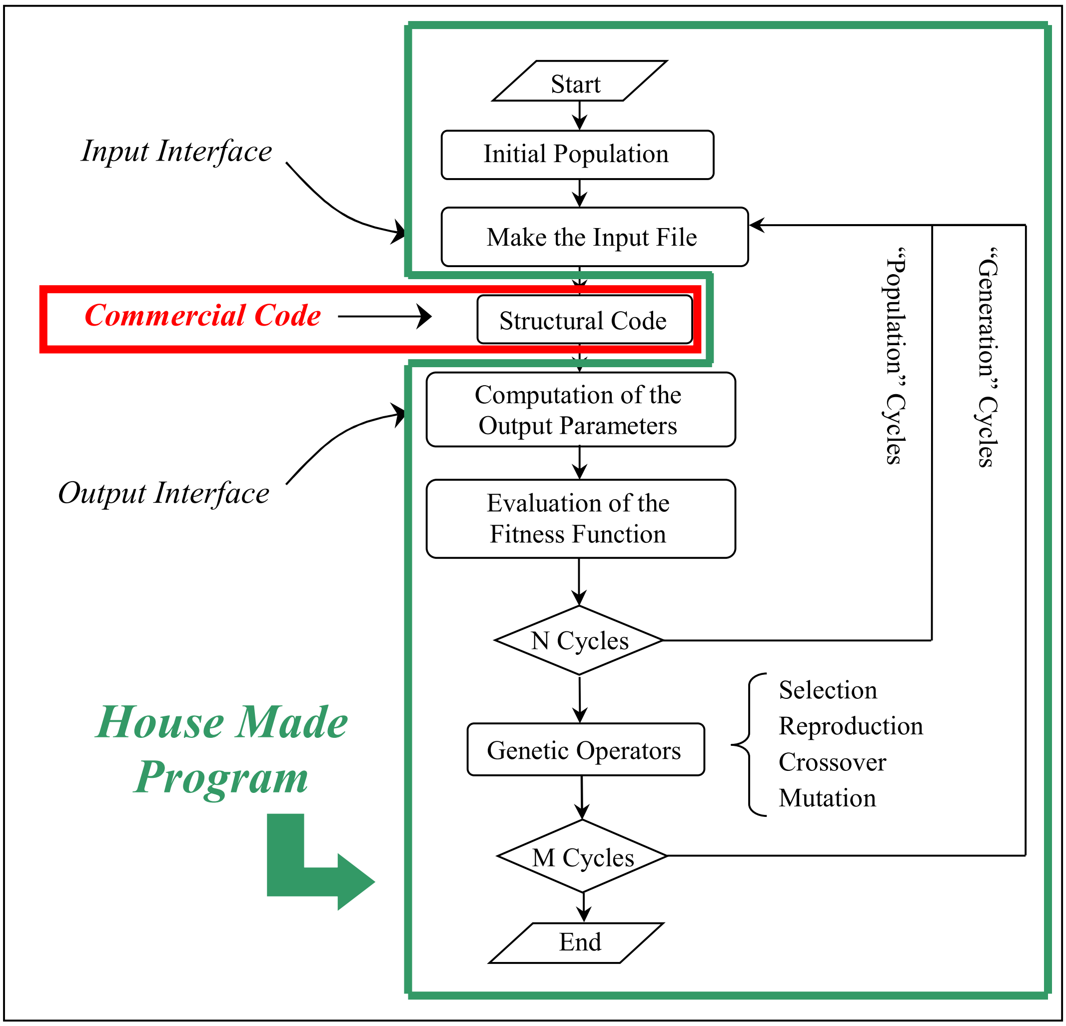

Figure 9: Flow-chart of the genetic algorithm analysis [11].

Regarding the dissipative device, one has assumed an elasto-plastic device with a response governed only by two mechanical parameters: the area of the device section and the yielding tension. Therefore, the optimization process will search the optimum values of these variables considering, as a fitness function, the amplitude of the displacement oscillation after the *40th* sec. (minimum problem).

With these data the genetic algorithm provides the optimum mechanical characteristics of area and yielding tension. Figure 10 shows the response of the system controlled by the dissipative devices optimized.

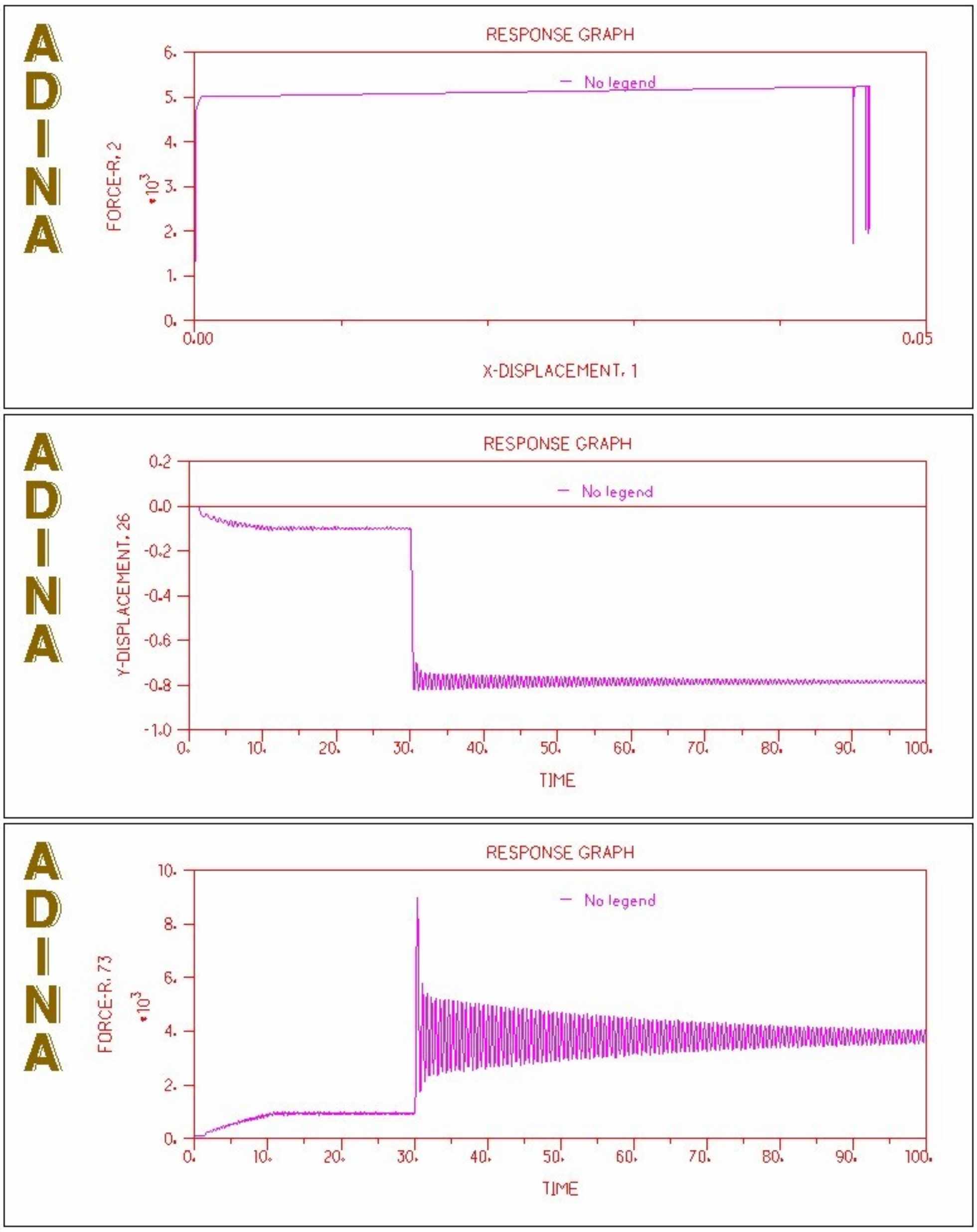

Figure 10: Plastic deformation of the dissipative device and time histories of mass displacement and anchorage force (controlled system).

The first graph of Figure 10 shows the displacement-force curve of the dissipative device and it is possible to note the high value of energy stored in the plastic deformations. The comparison between the graphs of Figure 10 and the graphs of Figure 8 shows a strong change in the dynamic response.

	Without d.d.	With d.d.	Difference (%)
Maximum displacement	*0.75 m*	*0.85 m*	*+ 13%*
Medium displacement	*0.50 m*	*0.80 m*	*+ 60%*
Oscillation amplitude	*0.40*	*0.05 m*	*- 87%*
Maximum axial tension	*13000 N*	*9000 N*	*- 31%*
Medium axial tension	*7000 N*	*4000 N*	*-43%*
Oscillation amplitude	*8000 N*	*1500 N*	*-81%*

Table 1: Comparison between the response without dissipative device (Without d.d.) and the response of the system with dissipative device (With d.d.).

Table 1 summarizes the comparison between the response evaluated on the system without dissipative device (Without d.d.) and the response of the system with dissipative device (With d.d.). One notes the great percentage gain regarding the axial force that is reduced of *43%* in the medium value and of *81%* in the oscillation amplitude. Therefore a proper design of the dissipation device plays a fundamental role to have a good behaviour of the whole safety system.

Conclusions

The paper investigates the dynamic response of a *Safety Line* installed on a new building by the Italian Society “Nouvo Modulo S.p.A.” The authors focus their attention on the role of the dissipative devices and put in evidence the reduction of the mass displacement and of the cable axial force. In particular a strong reduction (about 80%) is measured in the oscillation amplitude of the axial force. For these reasons the presence of the dissipative devices on a *Safety Line* is suitable to reduce the dynamic load on the anchorage.

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