Design optimization of tall steel buildings

L. Catallo & L. Sgambi
University of Rome "La Sapienza", Rome, Italy
S. Tranquilli
Structural Engineer, Rome, Italy

ABSTRACT: In this paper a micro-level optimization is applied to tall steel buildings. In order to achieve the optimum structure the Fully Stress Design technique is used to get the full section response. With this technique is possible to find the correct position of the horizontal stiffening that minimizing the structural weight. The restrictions on horizontal displacements must be taken into account during all the analyses.

1 INTRODUCTION

This paper deals with a micro-level optimization of tall steel buildings; in order to achieve the optimum structure, the Fully Stress Design technique is used to get the full section response. This technique has been applied to tall buildings, finding the correct position of the horizontal stiffening that minimize the structural weight, with respect of the limitation about horizontal displacements. The buildings with several a numbers of stories have been analysed for validation of the results.

2 DESIGN OPTIMIZATION

2.1 *Optimization problem*

If optimization can be considered as the search for the "perfect design", the different optimization techniques are the diverse paths able to reach the optimum point. Certainly this point cannot be reached, because it is impossible to get an optimum design under all points of view; however it is the idea that control the optimization methods. A simplified scheme of the optimization process is shown in Figure 1.

In all the optimum design procedures the modelization process is very important. In this process the real problem must be transformed into a mathematical problem, where the design parameters are present such as the variable vector. The model joints mechanicals, geometric and load variables with one or more objective functions and/or restraint functions.

The topic in the optimization process is the definition of the values of the variables, present in the variable list ($\underline{x}$), which minimize or maximize the object functions $F(\underline{x})$, under respect of the restraint conditions ($g(\underline{x})$ and $h(\underline{x})$ in Equation 1).

$$\begin{cases} \min F(x) \\ g_j(\underline{x}) \le 0 \quad j = 1...m \\ h_j(\underline{x}) = 0 \quad j = 1...k \end{cases} \tag{1}$$

The Fully Stress Design method (FSD) has been used in order to solve the optimization problem. This classic method is based on a optimality criterion. The optimization problem (Equation 1) is indirectly resolved by the FSD optimality criterion.

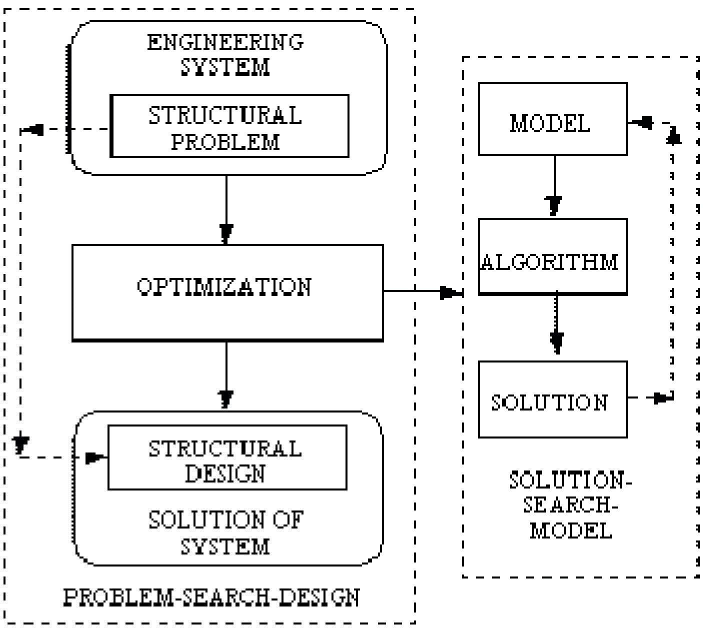


Figure 1. Optimization process.

2.2 *Fully Stressed Design*

FSD is a micro-level optimization method and its more important characteristic is the control of the stress state in some design section. If the beams have double T cross-section, it is possible to make a correlation between the geometric characteristics of a general section and the same characteristics of the reference section. These functions depend from the "omotetia" parameter a ($a = h_{\text{general section}} / h_{\text{reference section}}$), shown in Figure 2.

The correlation functions between the cross-sectional area (second moment of area) and the "omotetia" parameter is shown in Figure 3 (or in Figure 4 for the second moment of area). In this work IPE and HE-B beams have been investigated.

If the cross-section is subject to moments and axial forces, the top stress (s_{top}) and the bottom stress (s_{bot}) in the section are valuable by Equations 2 and 3 respectively:

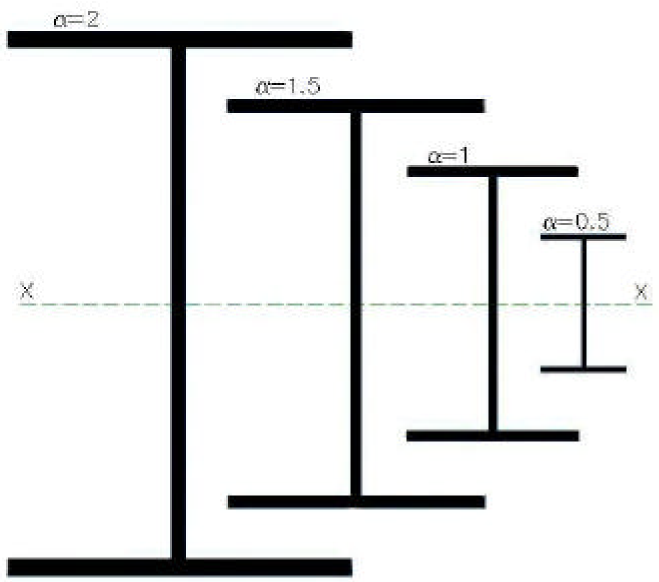


Figure 2. Example of different beam sections considered.

$$s_{top}(a) = \frac{N}{A(a)} - \frac{M}{W(a)} \tag{2}$$

$$s_{bot}(a) = \frac{N}{A(a)} + \frac{M}{W(a)} \tag{3}$$

Both these functions depend on parameter a.

The s_{top} and s_{bot} values must be limited between the values:

$$s^{-} \le s_{top}(a) \le s^{+} \tag{4}$$

$$s^{-} \le s_{bot}(a) \le s^{+} \tag{5}$$

Introducing Equations 4 and 5 in Equations 2 and 3 one obtains a four equations system providing at least one real solution:

$$\begin{cases} N \cdot W(a) - M \cdot A(a) - s^{-} \cdot A(a) \cdot W(a) = 0 \rightarrow a_1 \\ N \cdot W(a) - M \cdot A(a) - s^{+} \cdot A(a) \cdot W(a) = 0 \rightarrow a_2 \\ N \cdot W(a) + M \cdot A(a) - s^{-} \cdot A(a) \cdot W(a) = 0 \rightarrow a_3 \\ N \cdot W(a) + M \cdot A(a) - s^{+} \cdot A(a) \cdot W(a) = 0 \rightarrow a_4 \end{cases} \tag{6}$$

The design value is:

$$a_{design} = \max(a_i) \tag{7}$$

Using this procedure, one is able to achieve a dimensioning of the structure where the resistant capacity is better used.

The design is based on the resistant criteria, but the limit values s^{-} and s^{+} can be varied in order to take into account other structural criteria. In this case other criteria are indirectly satisfied by the FSD procedure.

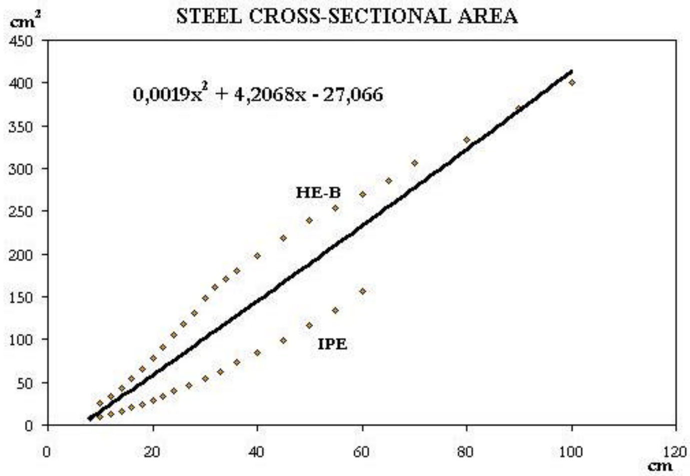


Figure 3. Relationship of steel cross-sectional area.

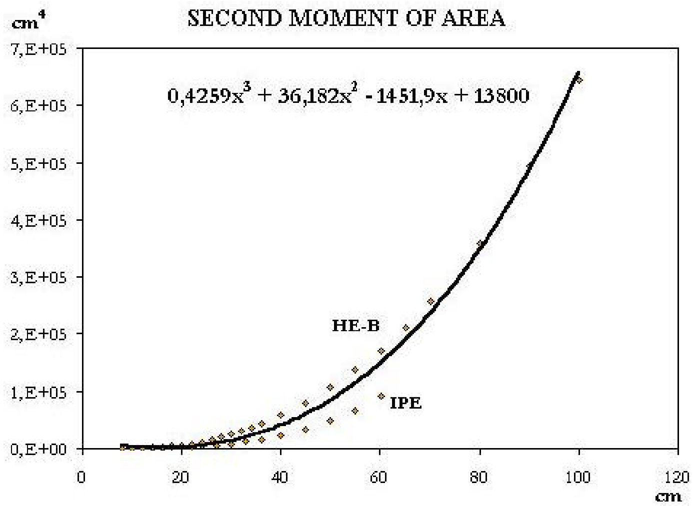


Figure 4. Relationship of second moment of area.

3 APPLICATIONS

In this chapter the FSD is applied in the design of tall building design procedure. The purpose of this study is to find out the correct position of the horizontal stiffening. The position and the design of these elements are very important in order to reduce horizontal displacements.

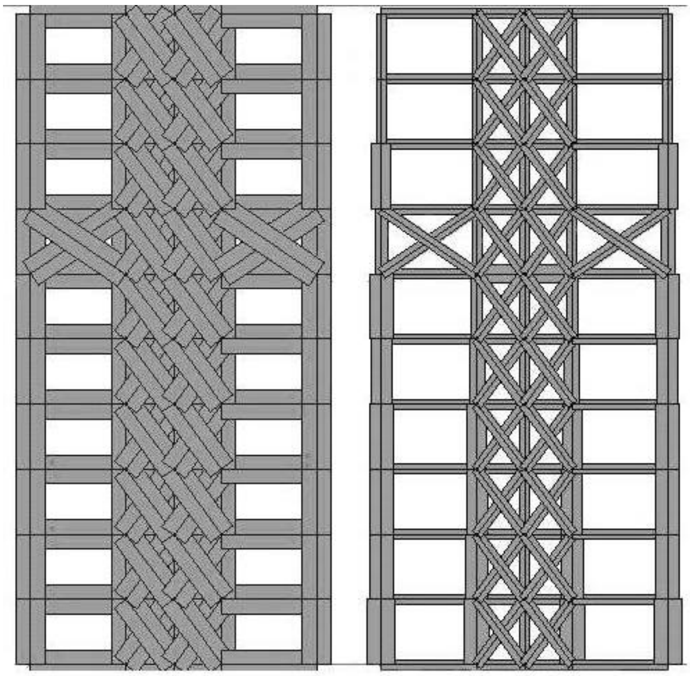
The total weight of the steel structure has been assumed as the objective function and the loads have been valued by the Italian Normative.

A planar frame with a number of stories variable from 10 to 40, subject to vertical and horizontal loads, has been investigated.

Two cases have been studied:

- One horizontal stiffening is present;
- Two horizontal stiffening are present.

For each case the problem studied is the definition of the correct position of the horizontal stiffening.



(a) (b)

Figure 5. Plane frame with ten-stories: a) before optimization; b) after optimization.

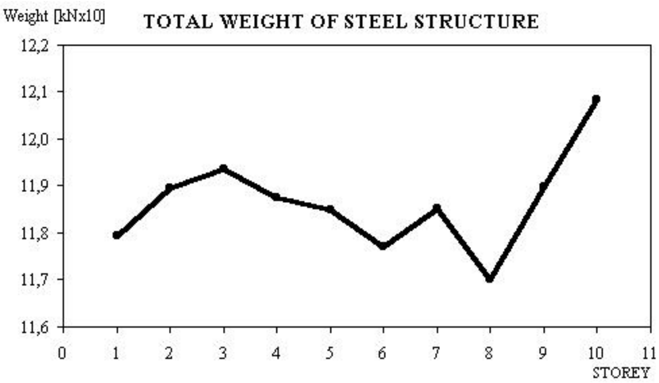


Figure 6. Relationship weight *vs* position of horizontal stiffening, for building with 10 stories.

3.1 *Search about optimal position of one horizontal stiffening*

As above-mentioned planar frames with 10, 20, 30 or 40 stories have been considered. For each case the correct position of the horizontal stiffening has been valued by the FSD. The 10 stories frame with the horizontal stiffening in the 7-th storey is shown in the Figure 5, before (Fig. 5a) and after (Fig. 5b) the FSD optimization technique.

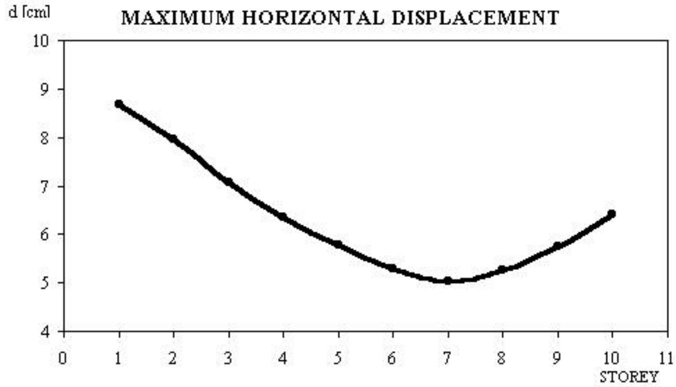


Figure 7. Relationship maximum horizontal displacement vs position of horizontal stiffening, for building with 10 stories.

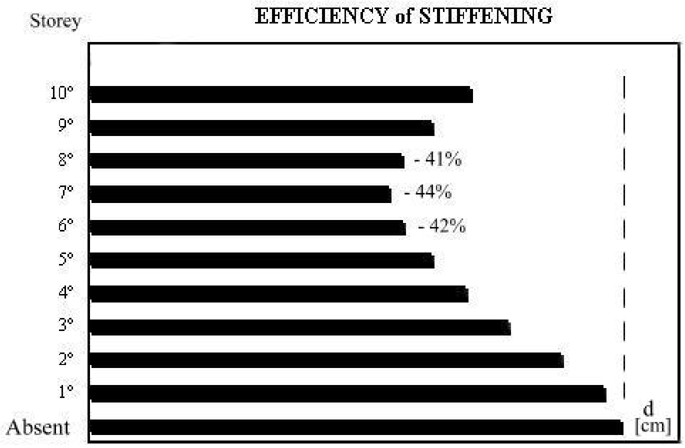


Figura 8. Efficiency of storey's stiffening.

For the 10 storey frame, ten cases has been studied: in each case the horizontal stiffening position is changed. The FSD procedure is applied in each case, in order to get always an optimization structure. Figure 6 shows the outcome of the FSD procedure in terms of the total structural weight. As we can see from this figure, the optimum position for the horizontal stiffening is the 8-th storey (80% of the total height of the frame). Figure 7 reportes the maximum lateral displacement when the horizontal stiffening position changes.

One can define a stiffening efficiency such as reduction of the massimum horizontal displacement compared to initial case of absence of the stiffening (as shown in Figure 8). In order to get the minimum horizontal displacement, the best position is in the 7-th storey where the horizontal stiffening decreases the horizontal displacement at the 44% respect at the original case. On the other hand, in order to get the minimum weight the best position is the *8* storey. However, in this case the stiffening efficiency decrease at *41%*.

Similar graphs have been obtained for frames with *20*, *30* and *40* stories. In the last case results are reported in Figure 9 (weight versus number of stories) and in Figure 10 (horizontal displacement versus number of stories).

Now the horizontal stiffening optimal position for the minimum weight and the minimum horizontal displacement position are different.

In fact, between the *18* and the *28* storey we have the minimum weight of the structure (*45-70%* of the total height) while the minimum horizontal displacement is achieve when the horizontal stiffening is between the *32nd* and the *36th* storey (*80-90%* of the total height).

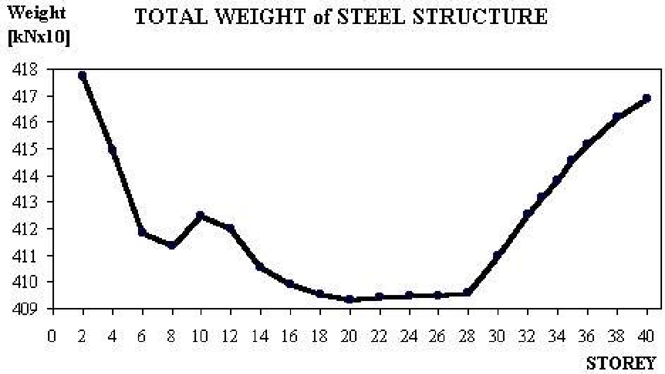


Figura 9. Relationship weight vs position of horizontal stiffening, for building with 40 stories.

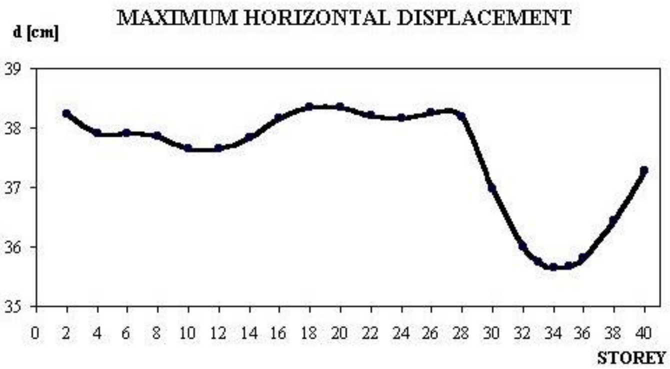


Figure 10. Relationship maximum horizontal displacement vs position of horizontal stiffening, for building with 40 stories.

As we can see from Figure 8 and Figure 11, if in the structure only one horizontal stiffening is present, its efficiency decreases when the number of stories increases. Therefore in tall buildings two or more horizontal stiffenings are need.

3.2 *Search about the optimal position of two horizontal stiffenings*

In this paragraph the tall building with two horizontal stiffening is studied.

A plane frame of *40* storeys, with base of *27 m*, a central vertical stiffening and three spans respectively of *5.5*, *5* e *6 m*, is investigated.

The objective function has been considered the total volume of the steel structure, and the optimal point represent the minimum weight design.

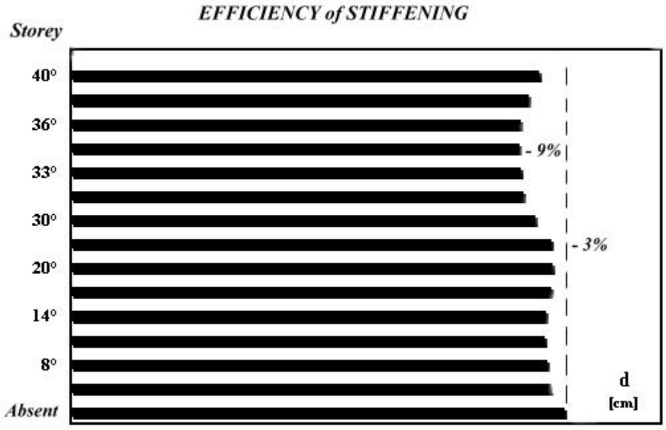


Figura 11. Efficiency of storey's stiffening.

The building has *40* stories, therefore *40 x 40 = 1600* cases with different horizontal stiffening position have been considered. The first result in term of the total weight versus horizontal stiffening position is reported in Figure 12.

Figure 13 shows the maximum horizontal displacement. In this case, figures are three dimensional surfaces because the dimension of the problem is increased.

The minimum displacement is achieved when the horizontal stiffening are in *30th* and *36th* story. As we can see from the Figure 12, when one horizontal stiffening is in the *36 th* story, the position of the second horizontal stiffening is little important.

4 CONCLUSIONS

In this paper the correct position of the horizontal stiffening has been studied in order to minimizing the total structural weight in the respect of the permissible horizontal displacement for tall steel buildings.

The work considere two cases, respectively with one or two horizontal stiffenings. For each case, the steel frame has been designed according to the FSD optimization technique.

From these studies, one can affirm that:

- One horizontal stiffenings:
  - The optimal position is between the 65% and the 85% of the total height of the structure.
  - The weight of structure increases quickly with the increase of the height of the building, because more stiffening is need in order to limit the horizontal displacements.
  - When the building is high only one horizontal stiffening is insufficient.

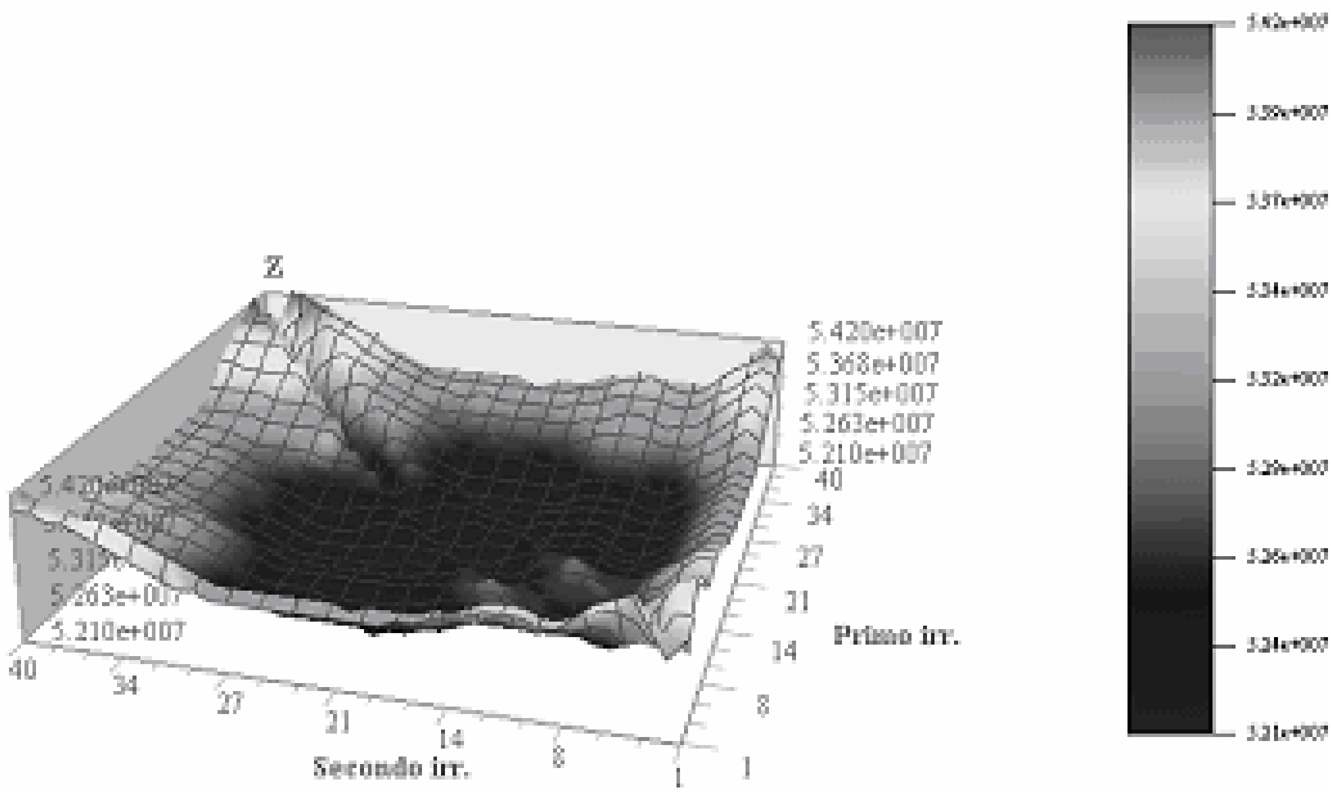


Figure 12. Surface of steel volume.

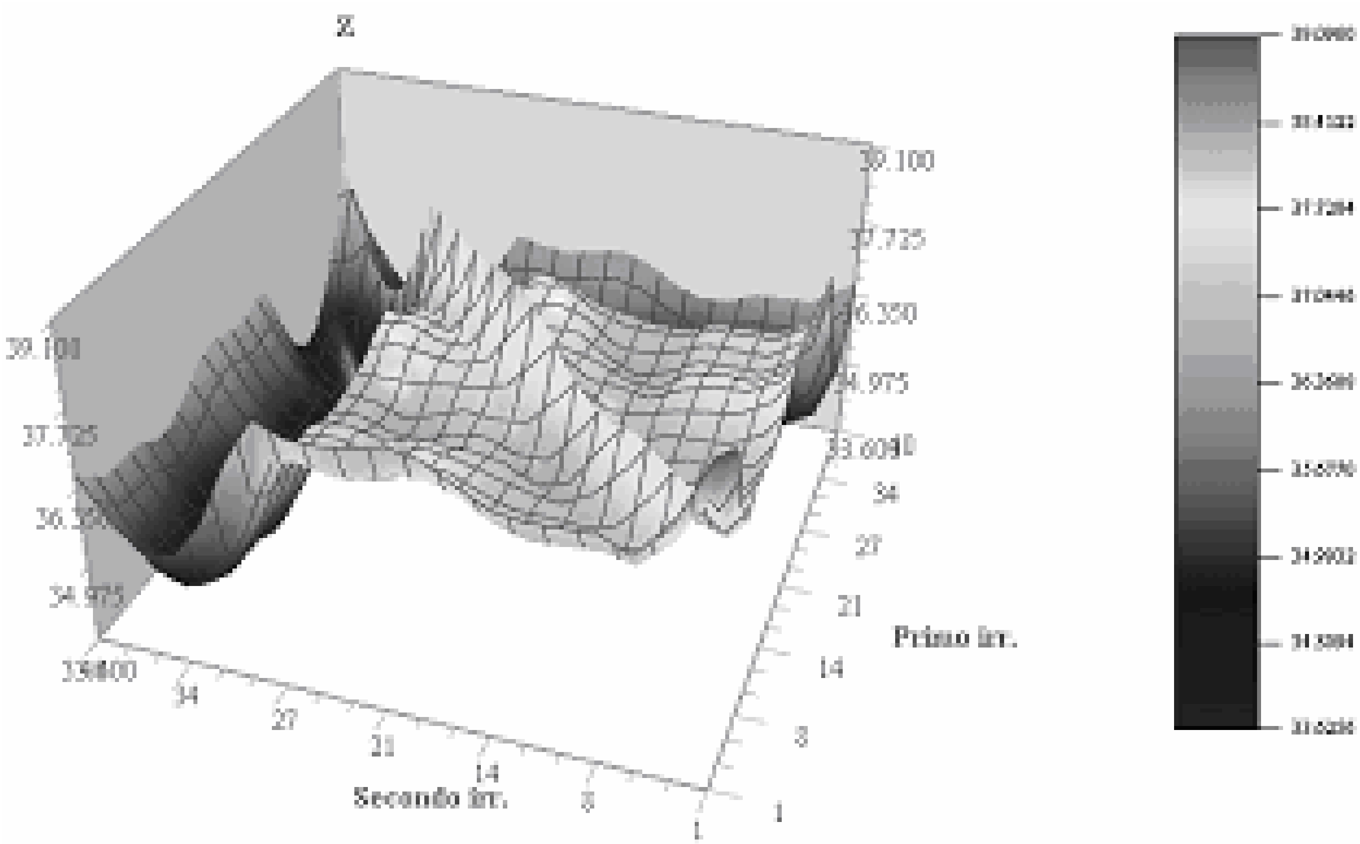


Figure 13. Surface of building’s displacements.

- Two horizontal stiffenings :
- In order to minimizing the total steel structural weigth the optimum positions for the two horizontal stiffening are the *30^th^* and *36^th^* story.
- when one horizontal stiffening is in the *36^th^* story, the position of the second horizontal stiffening is little important.

5 REFERENCES

Rao, S. 1996. *Engineering Optimization*. A Wiley.

Engel H. 1997. *Structure System*. Verlag Gerd Hatje.

Taranath, B. 1998. *Steel, Concrete and Composite Design of Tall Buildings*. McGraw Hill.

Arora, J.S. 1989. *Introduction to optimum design*. McGraw-Hill.

Engel, H. 1997. *Structure systems*. Matje Verlag.

Biondini, F., Bontempi, F. & Malerba, P.G. 2001. Bridges Emerging from the Structural Cooperation between Straight and Curved Superstructures. ISEC01, pp. 877-882.

Tranquilli, S. 2002. *The optimization process in the preliminary design of tall steel buildings* (in Italian). Graduate thesis. Rome. Italy.

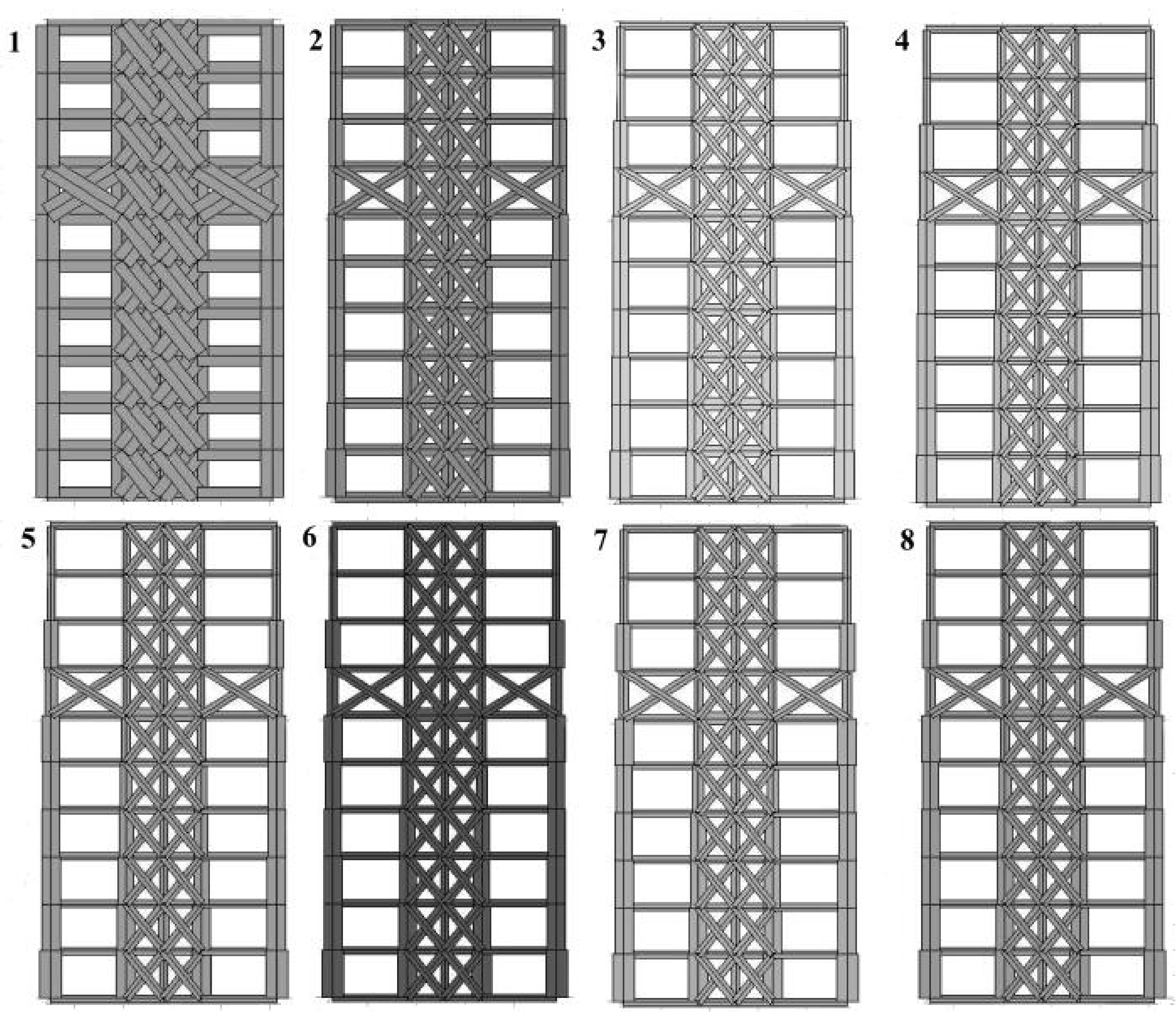


Figure 14. Optimization process of building.