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# Brâncuşi Endless Column: A Masterpiece of Art and Engineering

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**Abstract**

The Endless Column by Constantin Brâncuşi is "the most radical sculpture in the history of classic modernism", "the only one of modern times that can be compared with the great Egyptian, Greek and Renaissance monuments". It "is not only an artistic masterpiece, but also an extraordinary feat of engineering", the greatest example of collaboration between a sculptor and an engineer. This article illustrates the path that led the artist to conception of the column, its planning and construction, the investigations on preservation of the monument and its restoration, the aerodynamic tests in the wind tunnel, the modeling of the wind and the structure in virtue of which the aeroelastic instability, dynamic response and fatigue life were investigated. The conclusions discuss the column's role in the panorama of the great works of modern engineering.

**Keywords:** Aerodynamics, Art, Constantin Brâncuşi, Endless Column, Restoration, Wind Engineering

## 1. Introduction

Constantin Brâncuşi was born on February 19th 1876 in Romania, in the village of Hobita Gorj, near Târgu Jiu, and died in Paris, France on 16th March 1957. He spent his childhood between the village he was born in, Târgu Jiu, Slatina and Craiova, where he attended the School of Art and Crafts. In 1903 he was awarded his diploma from the National School of Fine Arts in Bucharest. The following year he left Romania and went to Paris, where he created a series of works that left an indelible mark on the history of art in the 20th century.

Brâncuşi's leading work, however, is judged by many to be the only one created in Romania and his only public work, the Târgu Jiu Memorial built between 1937 and 1938 to commemorate the resistance of the local population during the First World War. Among the buildings of the memorial the Endless Column, UNESCO World Heritage, stands out as "the most radical sculpture in the history of classic modernism", "the only one of modern times that can be compared with the great Egyptian, Greek and Renaissance monuments".

In order to build the column, a stele of 29.26 m in height with a slenderness ratio of 66, beyond the limits of its time and in large part current, Brâncuşi was assisted by an engineer, Stefan Georgescu Gorjan, with whom he gave life not only to one of the most celebrated works of art of all time, but to the greatest masterpiece arising from the collaboration between a sculptor and an engineer. According to UNESCO, "it is not only an artistic masterpiece, but also an extraordinary feat of engineering. Its dual function and its unique message make it imperative to make every effort to preserve it".

During the course of its existence the column has gone through various vicissitudes. With the Second World War over, in the era of communism, it was seen as a subversive symbol. Abandoned and even damaged, it survived thanks to the personal initiatives of the design engineer. When Ceausescu was deposed in 1989, Romania once more turned to look at preservation of the monument. It was the start of a long period of controversies, on the type of intervention to carry out, and through which one reached the restoration of 2001. Among other interventions it envisaged the restoring of the corroded zones of the spine, a reinforcement at the base of the spine to guarantee a level of safety to the wind actions coherent with the code prescriptions and re-plating of the coating modules, bringing them back to their original color.

In the period in which the restoration took place, a series of studies were begun on the actions and the effects of the wind, still in progress, aimed at verifying the real safety of the work. They showed that, at its origin, the structure possessed a more than adequate safety and that its reinforcement was not necessary. Above all they showed that the column not only represented a milestone of art and engineering, but it most likely translated the principle of perfect aerodynamic conception and the maximum synthesis between form and structure. Despite being endowed with such a marked slenderness as to potentially make it prey to the wind, thanks to its undulated edges the column has absolutely modest drag, it creates a greatly chaotic vortex wake and therefore being unable to induce violent transversal actions, it eludes every form of instability.

This paper illustrates the artistic path that led Brâncuşi

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to conception of the column (Point 2), its design and construction (Point 3), the investigations into preservation of the monument (Point 4) and its restoration (Point 5), the wind tunnel tests (Point 6), the modeling of the wind and of the structure (Point 7) by virtue of which the aeroelastic instability, the dynamic response (Point 8) and the wind-induced fatigue (Point 9) are investigated. The conclusions (Point 10) summarize the main results of the study and discuss the role of the column in the panorama of the great works of modern engineering.

## 2. Brâncuşi's Artistic Path

Constantin Brâncuşi (Tabart, 1995; Brezianu 1999), "the father of the modern sculpture", was born on February 19th 1876 in Romania, in the village of Hobita, Gorj, near Târgu Jiu, in an area known for its rich popular traditions of craftsmanship, above all for decorations carved in wood. His parents were very poor and he spent his infancy in a rural house.

In 1889 Constantin reached Craiova, where he worked in a bistro "The coloured star" (1892). In his free time he carved splendid wooden objects, above all a violin in pine wood. They were noticed by Ion Georgescu Gorjan, the owner of the bistro, who helped him to enrol in the School of Art and Crafts in 1894, where he passed his examinations and was admitted to the courses of specialisation in "wooden sculptures".

In 1898 Brâncuşi was admitted to the National School of Fine Arts in Bucharest, where he transferred once again thanks to the help of Ion Georgescu Gorjan and to a new evening job in a restaurant. Here he carved first *Vitellius* (1898) and *Head of Laocoon* (1900), then *Ecorché* (1901), "a man's statue with the skin removed that shows the muscular system and the ligaments" and the bust of his benefactor (1902) (Fig. 1).

Awarded his diploma in 1903, the following year Brâncuşi transferred to Paris. There, thanks to a small scholarship received from Bucharest, and to the by now usual

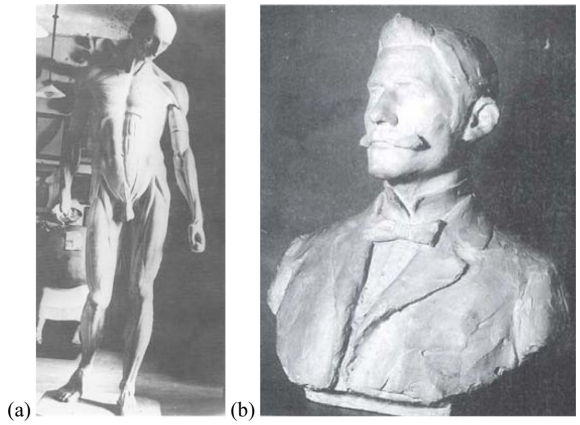


**Figure 1.** (a) Ecorché (1901); (b) bust of Ion Georgescu Gorjan (1902).

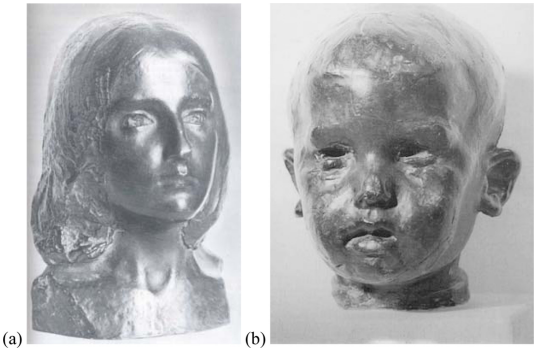


**Figure 2.** (a) Pride (1905); (b) L'Enfant (1906).

evening job in a restaurant, he enrolled in the School of Fine Arts and frequented Mercié's workshop. In this period he carved *Pride* and *L'Enfant* (Fig. 2). He exhibited them in the Show of the National Society of Fine Arts, where he was judged "one of the most gifted artists of the new generation", and at the Autumn Show, where he met Rodin. A brief period of apprenticeship began with the latter but from which he left after a few months stating that "nothing can grow under large trees".

He decided therefore to open his own first workshop in rue de Montparnasse, where he began to create sculptures and do inlay work. Here he created in the same year (1907), four fantastic works: *Torment, The Prayer, The Wisdom of the Earth* and above all *The Kiss* (Fig. 3), the first sign of an anti-naturalistic and anti-romantic turn, aimed at the stylization of clearly and essentially concluded volumes; on this line, Brâncuşi reached the definition of pure, impersonal, primordial forms obtained through a progressive

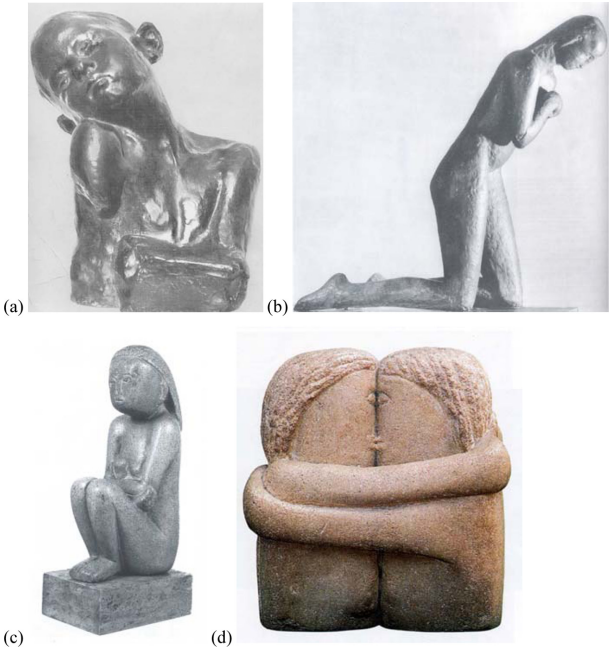


**Figure 3.** (a) Torment; (b) The Prayer; (c) The Wisdom of the Earth; (d) The Kiss (1907).

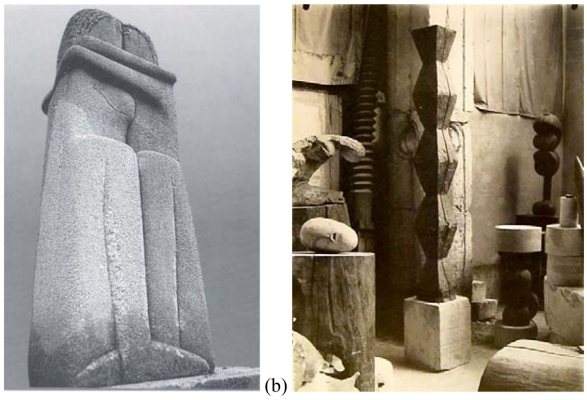


**Figure 4.** (a) The Kiss, Cemetery of Montparnasse (1908); (b) wooden column (1909).



**Figure 5.** (a) Maiastra (1910); (b) Miss Pogany (1912).

elimination of the accessory attributes. That is he tended "not to reproduce the external form but the idea, the essence of the things".

Brâncuşi once again took up the theme of *The Kiss* in 1909. Its first creation had a cubic form. That one in the cemetery of Montparnasse on the tomb of a young woman who committed suicide over love is more slender (Fig. 4(a)). The busts of the two bodies united by long arms recall the Romanian tradition according to which two trees planted at the sides of a grave evoke the strength of the love for eternity. This new version of *The Kiss* is the idealization and the prologue of the first wooden column, exhibited in 1909 at the Autumn Show (Fig. 4(b)).

Between 1910 and 1912 Brâncuşi created *Maïastra* and *Miss Pogany* (Fig. 5). The first is a golden bird that, in Romanian folklore, is able to change itself, to foretell the future, to bring separated lovers back together and to give sight back to the blind. With this representation Brâncuşi connected the notion of unity with that of metamorphosis, creating the first attempt to place his own sculptures in space. It also highlighted the first joining of the sculpture and the pedestal, one of the dominant themes of Brâncuşi's art: starting from the lower part, he tried to free himself from a material condition into a spirit that recalled oriental thought. The second represents a Hungarian girl who "inspired him by lowering her eyelids and by keeping her eyes half open". His success was by then overwhelming. He exhibited at the *Salon des Indépendants* together with Mondrian and Duchamp. He participated at the Armory Show in New York, contemporaneously exhibiting in Paris, London and Munich. He had his first personal show in the United States (1914).

Between 1913 and 1914, Brâncuşi carved *Le Premier Pas*, *Madame L.R.* and *Caryatid* (Fig. 6), his first wooden sculptures of African inspiration. They offered testimony of his new interest for primitivism and above all for Neolithic art. Rousseau said: "you want to turn antiquity into modernity".

In the same period Brâncuşi's exotic art blended well with the Romanian rustic tradition. Totemic columns were born, inspired by the funeral pillars of Transylvania (Fig. 7) and the superimposition of shapes that respect the spirit of the material. They are representations of the human body and new idealizations of the column that reappeared between 1917 and 1918. In 1920 Brâncuşi erected a column made up of 9 wooden modules in the garden of Edward Steichen (Fig. 8).

Brâncuşi's artistic line was defined by now. He accentuated his taste for abstraction, the search for the perfect and genetrix form that released stress and energy. He stuck with simple kinds of sculpture: the head, the stele

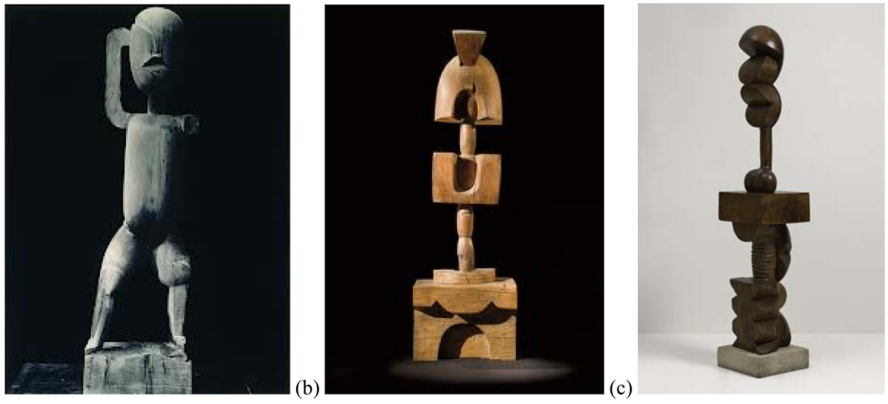


**Figure 6.** (a) Le Premier Pas (1913); (b) Madame L.R. (1914); (c) Caryatid (1914).

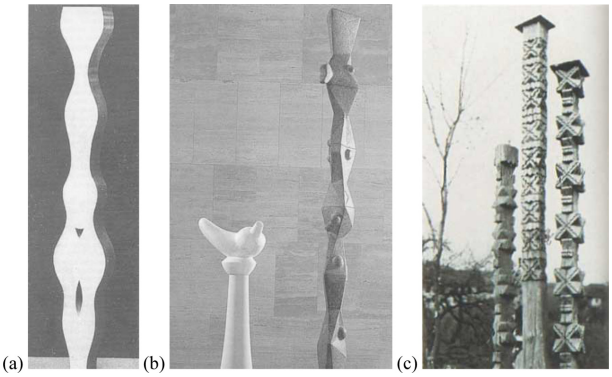


**Figure 7.** Totemic columns (a,b) inspired by the funeral pillars of Transylvania (c).



**Figure 8.** Column in the garden of Edward Steichen (1920).

and the caryatid. He worked with elementary shapes: the egg, the sphere, the cube and trapezoidal solids. He experimented with the interaction of such shapes with various types of raw and polished materials: stone, wood, bronze, brass and marble. Then he reached more complex aspects such as the combination of different elements or the multiplication of modular shapes. From here the superimposition of a principal shape on a plinth or the development of columns was born, in which Brâncuşi spasmodically sought the ideal relationship between the sizes of modules.

Between 1923 and 1925 Brâncuşi carved the *Bird in Space* (Fig. 9(a)), with which he continued his search for the pure shape. Starting again from *Maïastra* the ovoid shape became slender, the bird released its breath, the head and the legs joined in the verticality of the ascent and the body lost its own end. The quality of the bronze material and its shine made the shape of the bird immaterial and impalpable.

In 1931, by invitation of the Maharajah of Indore, he designed the Temple of Meditation in India, the conception of which evoked the pure and ovoid shape of the beginning of the world. There was a lake around which the three versions of the *Bird in Space* were placed - in white and black marble and polished bronze. In the centre of the temple there was the *King of the Kings* (Fig. 9(b)) originally called



**Figure 9.** (a) The Bird in Space (1923-1925); (b) The King of the Kings (1931).

the *Spirit of Buddha*. The work, never completed, incorporated the principle of essentiality, the integration of architecture, sculpture and furnishings, the poetic evocation of spiritual thought.

## 3. Design and Construction of the Endless Column

The idea of building the Endless Column in Romania dates back to 1921, when Brâncuşi proposed dedicating a monument to the memory of the heroes of the First World War. He returned to this idea in 1930, expressing the desire to erect a column at least 50 m high in a Bucharest square. Therefore, when in 1934 he was invited to design a monumental complex devoted to the resistance of the population of Târgu Jiu during the First World War, he made his dream come true near the place where he had been born.

Brâncuşi designed a complex set out along a line on the 45$^{th}$ parallel, the Avenue of Heroes (Fig. 10). The avenue began in a park on the banks of the River Jiu, near the Table of the Silence (Fig. 11(a)), a work formed by a low and circular table surrounded by 12 seats in the shape of an hourglass. It represents the circle that holds people together inviting them to silence and meditation. It recalls the flow of blood of the soldiers killed in war. From the Table of Silence the Avenue of Heroes leads to the Gate of the Kiss (Fig. 11(b)) at the opposite end of the park. Elegantly sculpted, it is the place where a man meets a

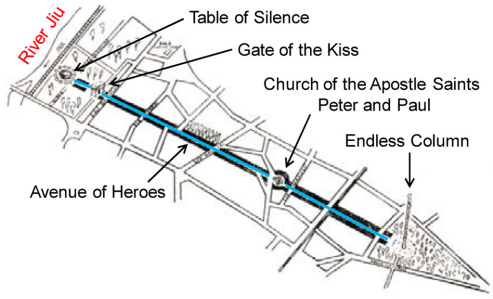



**Figure 10.** Monumental complex of Targu Jiù.

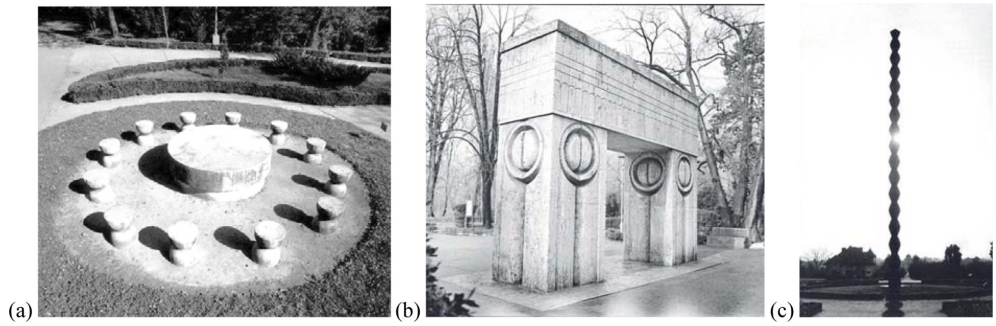


**Figure 11.** (a) The Table of Silence; (b) The Gate of the Kiss; (c) Endless Column.

woman and together they form a sacred union that represents the universe. This is the triumph of life over death. Beyond the Gate of the Kiss, the Avenue of Heroes leads to the orthodox church of the Apostle Saints Peter and Paul, then to a meadow, where the Endless Column (Fig. 11(c)) rises, initially called by Brâncuşi the "Column of Endless Gratitude" (Georgescu Gorjan, 2001; Andronescu and Melczer 2004).

To build the column Brâncuşi needed to have an engineer at his side. He was recommended the engineer head of the Central Laboratory of Petrosani, in Târgu Jiu. By a strange twist of fate, the latter was Stefan Georgescu Gorjan, the son of the owner of the "The coloured star" who had helped him in his early years. Brâncuşi was moved and appreciated both the professional skills of Stefan and his great general knowledge. In December 1934 Gorjan joined Brâncuşi in Paris and suggested: "fixing the base of the iron pillar in a thick foundation of concrete and inserting along the pillar identical modules of covering, whose overlapping would give the impression of continuity." Brâncuşi approved enthusiastically.

In the summer of 1937 Brâncuşi went to Târgu Jiu to choose the site for the column, then stayed in Gorjan's house in Petrosani, and together they worked for two weeks to reconcile the artistic vision, the technical aspects and the economic availability. Brâncuşi decided that the modules of the column would respect the law of plastic harmony, fruit of a long pathway of experimentation: their length was 4 times the smaller side and twice the longer one. He was instead very open on the technical questions that led to the choice that the column should be 29.26 m high. Having set this parameter, Brâncuşi and Gorjan agreed that the modules should have dimensions of 450 mm × 900 mm × 1800 mm (Fig. 12). The column therefore had a slenderness ratio of 66 with reference to the smallest size of the section, an exceptional value, beyond every custom, the limits of its time and to a large extent those of today.

In October 1937 the excavation of the foundations was carried out in the shape of the trunk of a pyramid. They were made up of two superimposed blocks of unreinforced concrete (Fig. 13(a)). The lower block, 2 m high, measured 4.50 m by 4.50 m in plan. The upper block, 3 m high, was of the "terraced" type and had three ledges that measured 4.00 m by 4.00 m, 3.50 m by 3.50 m and 3.00 m by 3.00 m in plan. The plate at the base of the spine was connected

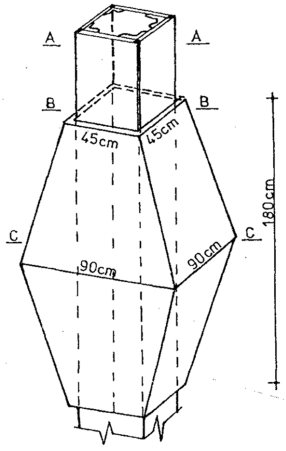



**Figure 12.** Modules of the column: law of plastic harmony.

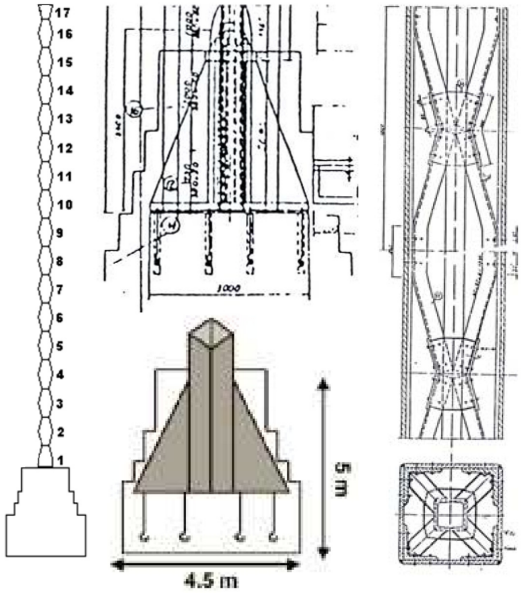



**Figure 13.** Foundation of the column: (a) concrete block; (b) connection between the base of the spine and the foundation by anchor bolts; (c) trellis made up of sections laid in a cross.

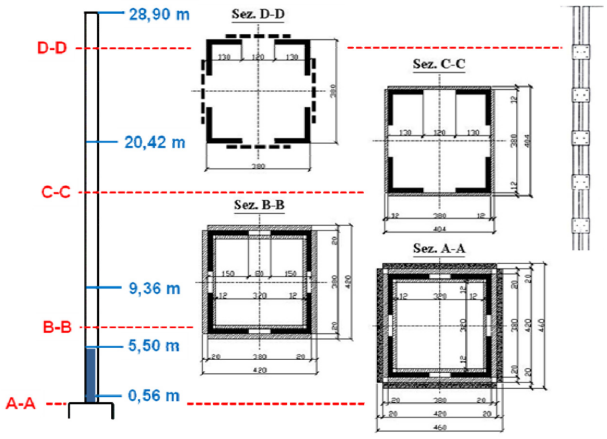



**Figure 14.** Steel spine of the column.

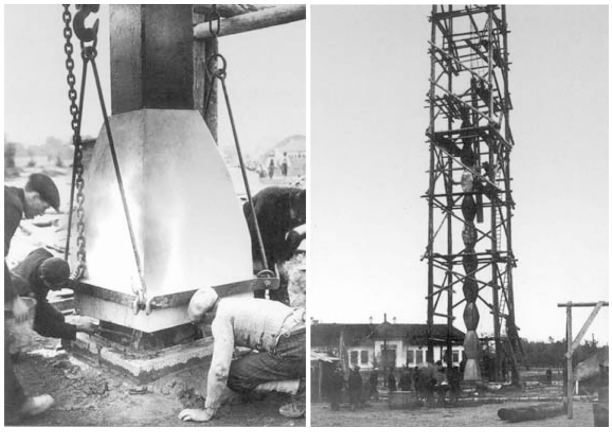


**Figure 15.** Phases of construction of the column.

with the foundation through 8 anchor bolts (Fig. 13(b)), anchored to the upper concrete block; they were also connected to a trellis made up of sections laid to form of cross, incorporated in the lower concrete block (Fig. 13(c)).

The spine, completed in mid-November, was created in three pieces welded on site to allow their transport. It consisted of a steel stem, 28.90 m in height, with a square cross-section of varying dimensions from 380×380 mm at the top to 460×460 mm at the base (Fig. 14). The summit tract with section D-D consisted of 4 angle brackets 130×130×16, connected by tie battens made up of plates 380×300×12. Below the height of 20.42 m, in the tract with section C-C, externally to the 4 angle brackets there were 4 rectangular plates 380×12. Below the height of 9.36 m, in the tract with section B-B, the 4 angle brackets became 150×150×18, the 4 rectangular plates become 380×20, internally to the angle brackets there were 4 rectangular plates 320×12. Below the height of 0.56 m, externally to the previous elements, there were 4 rectangular plates 420×20. The spine was filled with concrete up to the height of 5.50 m. The connections of the sections that made up the spine were carried out with rivets and bolts without nuts.

The modules placed on the spine were of cast iron. Each module consisted of two trunks of a square base pyramid, joined in correspondence of the largest bases. The edges of the pyramid trunks were not rectilinear, therefore the faceting of the modules was curved and different for every facet. The cast iron was painted internally and externally plated with thin layers of zinc, brass and a protective lacquer that gave it a yellow-gold aspect.

All in all 15 complete modules were created plus two half end modules (Fig. 15). Thanks to them, unlike ancient columns with a base and a capital, the column had neither a beginning nor an end. The semi-module at the base was made up of a trunk of a pyramid 90 cm high, the larger base of which continued in a prism with a square base to an overall height of 136 cm; thanks to this, the column seems firmly anchored to the ground. At the top the semi-module is made up of a trunk of a pyramid topped by a cover; seen from below it seems smaller and transmits a sense of perpetual incompleteness and potential endless continuation in space. The modules were connected to the spine by means of metallic connectors that allowed transfer of the horizontal forces but not the vertical ones. The modules were not bonded to one another.

The assemblage of the modules was completed in June 1938. The column was inaugurated in October 1938. Having completed the column, Brâncuşi left Romania never to return. His life stayed rich in successes but at the same time it became more and more solitary and isolated. On March 16th 1957 he died in Paris at the age of 81.

The Endless Column once more took up the idea of the "*axis mundi*" that sustains the vault of the heavens and connects the earth to the sky. Through the column, symbol of "ascension" and "transcendence", man raises his own spirit, he reaches absolute freedom and beatitude, rejecting every form of conditioning. According to Brâncuşi it was a "stairway to Heaven" destined to the souls of dead soldiers. It reproduced a movement upward and "a cosmic infinity" that transcended the force of gravity and the mortality of man. According to critics it is the only sculpture of modern times that can be compared to the great Egyptian, Greek and Renaissance monuments, although it looks to the future from the pedestal of a new era of sculpture that is deeper, freer and more abstract. It is "the most radical sculpture in the history of classical modernism". It cuts the history of sculpture in two, setting the beauty of this Romanian genius on the border between the classical era and the modern one.

## 4. Preservation of the Column

With the Second World War over, the era of the communism prevented Brâncuşi, defined an "undesirable person" from returning to his country. The column was seen as a subversive symbol. Stefan Georgescu Gorjan was imprisoned and sent to do forced labor. Many documents collected on the column were destroyed. In 1953 the mayor of Târgu Jiu had a cable attached to a tractor and had the

column pulled to try to topple it. The attempt was not successful, but the spine and the foundations were damaged.

When Gorjan returned to liberty he devoted the rest of his life, at his own expense, to maintenance of the work. He had the column re-plated between 1965 and 1966. He repeated this operation in 1976 at the time of the centennial of the birth of Brâncuşi. UNESCO proclaimed 1976 "international year of Brâncuşi".

In 1984 the Romanian institute for Research on Constructions (INCERC) compiled a report in which it supplied accurate measurements of the construction. Another INCERC report supplied the results of measurements that estimated a fundamental period of vibration equal to 1.8 s. The damping was not measured. In the same report the consequences of the pull of 88 kN caused by the cable towed the tractor in 1953 were examined. It estimated a tilt of 7°, with a shift of 21 cm at the summit.

In 1985 a technical committee studied the conditions of preservation of the Column. It defined the behaviour of the monument over the years excellent and stated that its maintenance required at most protective measures against corrosion (Fig. 16) (Georgescu et al., 1986). Gorjan died 2 months later, on March 5th 1985, happy about the interest of his country regarding the masterpiece.

In 1989 Ceausescu was deposed and Romania went back to looking at the preservation of its monuments. "We want to restore everything", said Radu Varia, a famous Romanian art critic and expert on Brâncuşi, who set up the Constantin Brâncuşi International Foundation in New York in 1991 and proposed a plan of restoration for the column. The following year Varia managed to have the memorial of Târgu Jiu declared by the Romanian government a "monument of public utility and national interest". Just as Varia wished, in May 1996 the column was listed in the World Monuments Watch of the first 100 world monuments to which to destine World Monument Fund (WMF). At the same time Romania asked UNESCO for the column to be placed in the World Heritage List.

Everyone agreed on the decision to restore the monumental complex and above all the column. They all appreciated Varia's initiatives. However, his ideas on the type of restoration created enormous controversies. Varia sustained that when the column had been built it was a fable of engineering; over time, nevertheless, condensation had formed on the inside that had damaged it. For this reason he wanted to clean up and restore both the interior and the exterior using a different coating than brass. He wanted to install sensors inside the column to monitor the temperature and the humidity. He wanted to replace the corroded spine with a column in stainless steel. He wanted to rebuild the foundations.

That was the beginning of a battle of opinions. Many followed Varia in the idea of replacing the spine. Others sustained that such an intervention would de-naturalize and deface the monument. Above all Sorana Georgescu Gorjan, the design engineer's daughter, defended the identity of the monument, saying that to destroy even just one element of the column would be the same as destroying it.

Despite this, in September 1996 the modules of the column were dismantled for a deeper and closer examination. Initially the spine was abandoned for many months in the rain and snow, as evidence that its substitution was by then taken for granted. Later it was wrapped in an ineffective and even more harmful plastic sheet: the covering held in the damp and encouraged corrosion. This worsened the consequences of a previous intervention: the plugging of a hole in the semi-module of the summit that favored the internal circulation of air.

Towards the end of 1996 the competence of Varia to administer the project and his methods were brought into discussion by the Romanian Government. The modules were heavy and the crane used for dismantling them, of insufficient height, damaged several of them. To overcome the difficulties, some of these were dismantled with a sledge hammer. Only at a later time did he resort to scaffolding. The situation worsened when Varia removed some steel samples from the spine to perform metallurgical studies (Fig. 17). The results were not published; the pieces removed disappeared and had to be recast and welded to close the holes.

At the beginning of 1997 new metallurgical analyses were carried out that showed that the steel was not of high strength and possessed minimal quantities of carbon, sulfur and phosphorus. The yield strength was included between

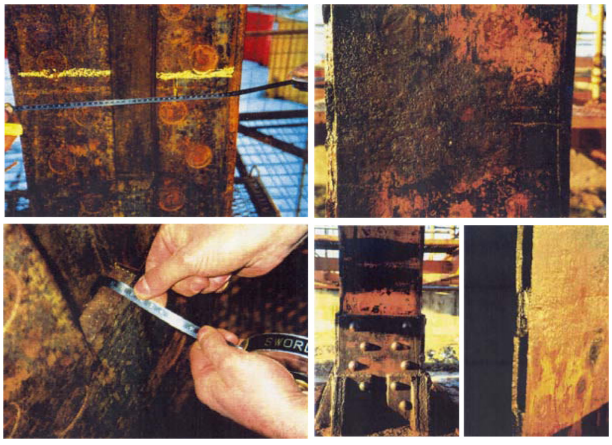


**Figure 16.** State of preservation of the column (1985).



**Figure 17.** Bored mudulus.

229 and 262 N/mm$^2$, the ultimate strength between 318 and 411 N/mm$^2$; so the material, classified as type OL 37-2 according to the Romanian code, could be likened to Fe360 steel according to Eurocode 3 (2005a). Similar examinations showed that the preservation of the modules was satisfactory and that the plating performed by Gorjan had protected the base material well. Instead, the initial color had completely disappeared.

On the other hand worries were raised by a report on the resistance of the spine compiled by INCERC in September 1997. An analysis of the free vibrations confirmed that the fundamental period was equal to 1.8~1.9 sec. The actions of the wind were calculated with the Romanian, American, Canadian codes and with Eurocode 1 (2004). Operating with the admissible stress method, for wind perpendicular to a face the safety coefficient was equal to 1.43; for diagonal wind it was included between 0.98 and 1.08. Repeating the analyses bearing in mind the corrosion, the safety coefficient respectively reduced itself to the values of 1.35 and 0.93~0.98. Apprehension over these results was partially mitigated by the fact that the structure had existed without problems for 60 years.

In the spring of 1997 the WMF renewed its support to Romania for the restoration of the monument, but asked to examine Varia's much discussed project. Following such request the Romanian Ministry of Culture asked for the intervention of UNESCO, which sent a delegation of experts to Romania, from November 30$^{th}$ to December 5$^{th}$ 1997, which compiled a preliminary report in January 1998. Sometime later UNESCO sent a second delegation of experts to Romania; in May 1998 it compiled a document (Croci et al., 1998) that represents a milestone in the history of the monument.

The document began by examining the 3 solutions proposed by the Romanian experts: A) the modules are not removed; B) the modules are removed but the spine stays intact; C) the modules are removed and the spine is replaced with a new one in stainless steel. Going back to the calculations of INCERC, the committee observed that the spine had a resistance inferior to that required by the regulations. Therefore it acknowledged that solution C) was technically the best. On the other hand it pointed out that science and technology must place themselves at the service of culture, and that separate pathways cannot be undertaken to reach the dual purpose of guaranteeing safety and the authenticity of the work. Therefore the committee proposed a fourth solution D) which consisted of restoring the spine without replacing it; it foresaw 9 points: a) dismantling the spine; b) examination of its internal surfaces; c) installation of the elements of the spine in a laboratory; d) sandblasting and painting to eliminate the corrosion; e) reinforcement of the spine; f) treatment for protection against corrosion; g) remounting of the spine; h) maintenance; i) plating of the modules.

As regards the spine, the committee suggested increasing the resistant section of the corroded zones adding new original steel plates to the elements inside the spine so as not to modify its external dimensions. As regards the modules, they recommended balancing the repair and the preservation of the original surfaces, suggesting caution about excessive restoration; for the plating, they also recommended using methods respectful of the technical limits in place in 1936 and that the choice of alloy maintained the original color.

In conclusion the report declared that the column was a work of art of engineering and recommended making every effort to preserve its "artistic value, potential unity and integrity". Thus the committee agreed that substitution of the spine would destroy the artistic value of the column, since the criterion of authenticity would no longer be valid.

On the provisions of this document the Romanian Government paid for new tests on the spine. They showed that the plates did not have any fractures. Of 8 welded joints examined none showed cracks. The steel had low carbon content, a limited tendency to form cracks and fractures and was easy to weld. The welds were not with complete penetration. Of 100 bolts examined, only one was broken. From the point of view of corrosion, the spine was in much better condition than expected. The spine was in a more suitable condition to be preserved than to be replaced.

## 5. Restoration of the Column

Once it had been established that Varia's scheme of restoration was based on wrong assumptions, the WMF recommended adoption of a project of intervention inspired by the guidelines contained in the report from UNESCO. To allow everybody to express their own ideas, it also organized an international conference in Târgu Jiu and Bucharest, from June 2$^{nd}$ to 4$^{th}$ 1999, to identify a scheme of restoration that was not invasive (Treatment, 1999).

In 1999 Romania gave up the idea of replacing the spine. The World Bank financed Romania with $2 million to restore the monument without replacing it. UNESCO declared the Column "World Heritage" stating that "it is not only a masterpiece of modern art, but also an extraordinary enterprise of engineering. Its double function and its unique message make it mandatory to make whatsoever effort to preserve it". Unfortunately the fund allocated by the World Bank was almost entirely used, once more, to solving the problem of corrosion, relegating the structural aspects to a marginal role.

On December 30$^{th}$ 1999 the Romanian Ministry of Culture and the Union of Plastic Artists (UAP) signed the contract of restoration-consolidation of the column. In January 2000 their guidelines were issued for the restoration (Crisan, 2000). On January 24$^{th}$ 2000 Dan Lungu, a professor at the Technical University of Civil Engineering, Bucharest and recently made director of INCERC, compiled a new report on the actions and the effects of wind on the column (Lungu, 2000), which mitigated the previous results on the safety of the work, besides confirming some criti-

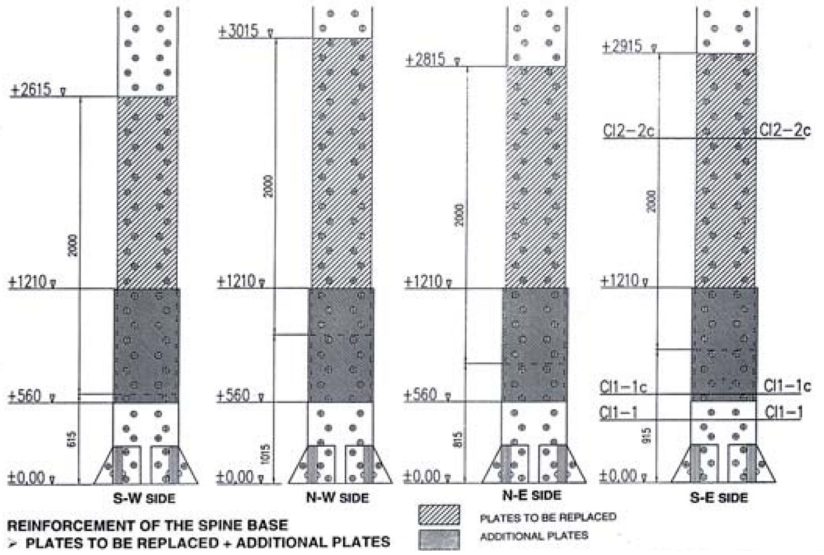



**Figure 18.** Project of the intervention at the base of the spine.

calities. Applying the new American standard, not yet issued, the spine was verified; applying Eurocode 1, the stress exceeded the yield strength by 25% in the sections at the height of 55 cm and 125 cm.

On the basis of Lungu's document, in February 2000 the strategy for structural recovery was outlined (Crisan and Dogariu, 2000). The objectives of the intervention were: 1) to bring the spine to its initial structural parameters verified on site for 63 years; 2) to increase the resistance and the stability of the original spine with regard to the actions of wind and earthquake. The operations to achieve such objectives consisted of: 1) strengthening the lower part of the spine and replacing the welds; 2) creating a system of damping inside the spine. The reinforcement at the base of the spine envisaged (Fig. 18): 1) replacing the 4 slightly corroded external plates between the heights of 1.21 and 2.62 m, with 4 identical plates (22×378×2000 mm) made of type OL 52 steel corresponding to Fe 510 steel; 2) externally applying an additional collar to the spine made up of 4 plates 20 mm thick, between the heights of 0.56 and 1.21 m. The intervention also envisaged a check and if necessary the replacing of the horizontal welds between the plates. It was proposed to study the damping system at a later time, only if necessary.

On July 3rd 2000 Lungu sent me a fax in which he told me the vicissitudes of the column and he explained that he had succeeded in blocking the idea of replacing the spine accepting small interventions of reinforcement even though not proven by in-depth analysis as the work would require. He thus asked me to carry out advanced analysis that might possibly show that the aerodynamics of the column was much better than estimated with conventional methods. He was convinced that the genius of Brâncuşi has been able to create not only an artistically perfect shape, but also so efficient as to render the actions of the wind minimum. We met in Genova at the beginning of August.

In Genova I expressed my doubts to Lungu on the reliability of the structural analysis on the action of the wind, carried out using standards clearly inapplicable to such a particular structure. I also expressed my worries about the lack of analysis on the crosswind response, parti- cularly on vortex shedding and galloping. The fact that the column had survived more than 60 years was only a motive for partial comfort: with respect to phenomena with potentially catastrophic consequences such as vortex shedding and galloping, it was necessary to investigate the effects of events with at least 500~1000 years of return period.

At the end of our meeting we compiled a program for the studies to be carried out; they included full-scale measurements, wind tunnel tests, analysis of the dynamic response and the aeroelastic behavior, evaluation of the wind-induced fatigue and of the structural reliability. Lungu was convinced that the Romanian ministries and banks would be willing to finance such an important study. At the beginning of September, we signed a declaration of intent between the University of Genoa, INCERC and the Rumanian Ministry of Culture.

The restoration work began on October 1st 2000 and was

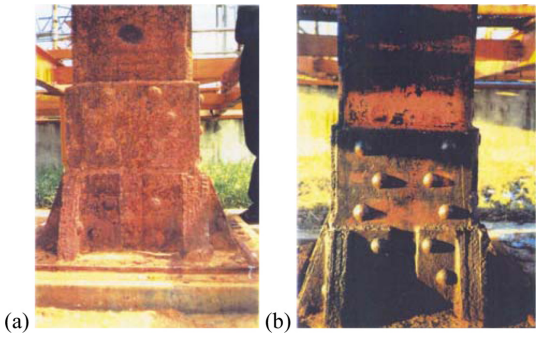



**Figure 19.** Base of the spine before (a) and after (b) the intervention.

completed on December 15th (Milligan and Tully, 1995; Parigoris, 2002). The structural solution, coherent with the UAP report (Crisan and Dogariu, 2000) (Figs. 19 and 20), was approved by the World Bank and by the Romanian Ministerial Committee for Historical Monuments. The ornamental modules were endowed with a protective covering and with a shiny bronze finish of golden color that replicated the original (Fig. 21). They were not bonded to one another but connected with silicone to better absorb the movements induced by the wind and possibly by an earthquake. A system of ventilation at the base of the stem and a device for protection from lightning were also created (Fig. 22).



**Figure 20.** New steel plates.



**Figure 21.** Restoration of the modules.

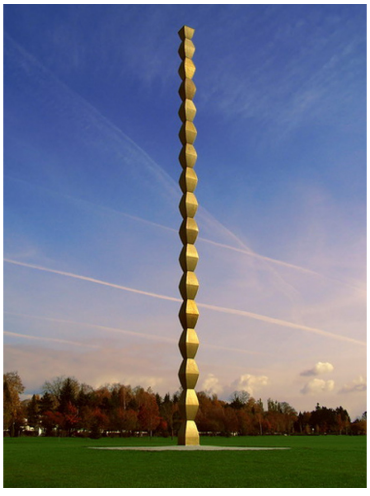


**Figure 22.** Endless Column at the end of the restoration works.

The monitoring and dynamic identification of the Column were often carried out at night so as not to hinder the restoration work. The investigations made use of environmental vibrations taken with a measuring system of microtremors (Lungu et al., 2005). The measurements were taken after the sealing of the joints with silicone.

The vibrations of the spine without the ornamental modules were measured on November 3rd. The first and second natural periods were respectively 1.205 s and 0.268 s; the damping coefficients of the first two modes were respectively 0.0082 and 0.018. The vibrations of the column complete with the modules were measured on November 14th. The fundamental period was 1.949 s; the damping coefficient was included between 0.0159 and 0.0193 as a function of the direction of vibration. The presence of the modules increased both the period and the damping; so the modules did not have merely an ornamental role, on the contrary they developed an important structural function. It is worth noting that the sealing of the modules with silicone probably reduced the dissipation in comparison to the original state of the column, when the modules were not connected.

Unfortunately, despite the signature of the declaration of intent, reality showed itself once more different from what had been expected. Many months passed in which the government and the Romanian banks took their time over the decision to destine resources to the study of wind actions. When it was clear that this would not happen, curiosity to understand the behavior of the column was so great that I decided to start the study out of pure scientific interest. In this way, in April 2001 an experimental, theoretical and numerical research began that is still in progress. At first it focused on the behavior of the monument in its real configuration; later it was extended to the spine deprived of the covering modules, a condition in which the column has been left for long time.

## 6. Wind Tunnel Tests and Aerodynamic Properties

The experiments on the column with the covering modules were carried out in April 2001 in the open circuit wind tunnel of CRIACIV, with a test section of 2.4×1.6 m (Solari et al., 2002). Tests were performed in smooth flow, on a 1:6 rigid sectional model including three modules (Fig. 23), with a span length 900 mm. The model, put horizontally with respect to the flow, was sustained between two rectangular end-plates, so to get an approaching flow

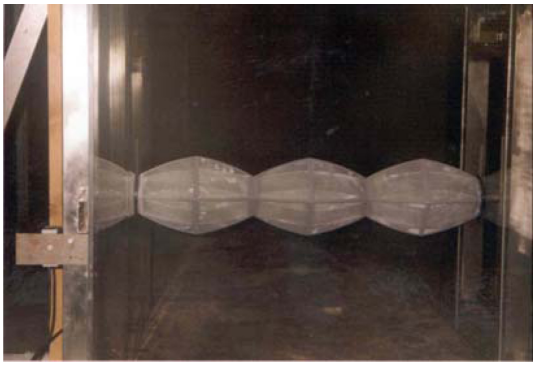


**Figure 23.** Sectional model of the column in the wind tunnel.

with no appreciable 3-D effects. The model structure consisted of a rigid circular steel arm; the appropriate shape of the cover elements was obtained through Plexiglas curved surfaces, fixed to rigid Plexiglas ribs. The supporting arm was restrained by 6 steel trusses connected to as many load cells. The signals from the 6 cells were acquired with sampling frequency 1000 Hz.

Let $X$, $Y$ be a couple of Cartesian axes parallel/perpendicular to the sides of the column. Let $x$, $y$ be a couple of Cartesian axes rotated the angle of attack β with respect to the axes $X$, $Y$; $x$ is aligned with the mean wind velocity $\overline{u}$ (Fig. 24). Let $D$ and $L$ be the drag and lift force per unit length, along $x$ and $y$ respectively, measured by the load cells. From such measures the following drag and lift coefficients, Strouhal number and rms value of the lift coefficient were obtained:

$$c_D=\frac{\overline{D}}{\frac{1}{2}\rho\overline{u}^2 b};\quad c_L=\frac{\overline{L}}{\frac{1}{2}\rho\overline{u}^2 b};\quad S=\frac{n_s b}{\overline{u}};\quad c_{Lrms}=\frac{\sigma_L}{\frac{1}{2}\rho\overline{u}^2 b} \quad (1)$$

where $\overline{D}$ and $\overline{L}$ are the mean values of $D$ and $L$, $\sigma_L$ is the root mean square (rms) value of $L$, $\overline{q}=\rho\overline{u}^2/2$ is the mean velocity pressure, $\rho$ is the density of air, $n_s$ is the vortex shedding frequency obtained from the power spectral density of $L$, $b$ is the reference size of the section, in this case the maximum width $B$ of the covering modules ($b=B=900$ mm in full-scale).

The approaching wind speed was varied in the range 10 to 20 m/s, in order to check for possible Reynolds number effects. In this case, they are almost negligible. The relative angle of attack β of the wind was varied by rotating the model from –55° to +55°, with steps of 5°. Smaller steps

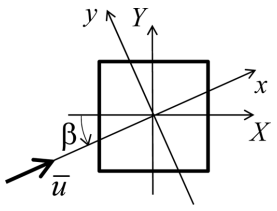



**Figure 24.** Reference system and wind direction.

for β were adopted close to 0° and 45°. Figure 25 shows the diagrams of $c_D$, $c_L$, $c_D+c'_L$, $c'_D-c_L$, $S$ and $c_{Lrms}$, as functions of β; $c'_D=\partial c_D/\partial\beta$ and $c'_L=\partial c_L/\partial\beta$.

The experiments on the column without the covering modules were carried out in the closed circuit wind tunnel of the Faculty of Engineering of the University of Genova, with test section 1.7×1.35 m. Two configurations were studied (Fig. 14): 1) a prismatic element with square section, representative of sections A-A, B-B and C-C of the spine and of the section D-D wrapped in a plastic sheet; 2) the part of the spine with section D-D, constituted by 4 angle brackets connected by batten plates.

The aerodynamic properties of the prismatic element with square section, also documented in several scientific papers, were determined between the end of 2011 and the beginning of 2012 during a test campaign aimed at studying, more in general, the role of rounded corners (Carassale et al., 2012). Tests were performed in both smooth and turbulent flow on rigid sectional models composed by the assemblage of aluminum plates; the models had a span length 500 mm and were mounted in cross-flow configuration on a force balance realized by 6 load cells. End plates were installed at the extremities of the models to maintain two-dimensional flow conditions (Fig. 26). In order to explore possible Reynolds number effects, herein almost negligible, tests were carried out varying the wind-tunnel velocity in the range between 5 to 25 m/s and the side $l$ of the element in the range between 60 to 150 mm. The relative angle of attack β of the wind was varied by rotating the model from –5° to +50°, with steps between 2° and 5°. Signals from the 6 cells were acquired with sampling frequency 2 KHz. Similarly to Fig. 25, Fig. 27 shows the diagrams of $c_D$, $c_L$, $c_D+c'_L$, $c'_D-c_L$, $S$ and $c_{Lrms}$ as functions of β in smooth flow conditions. These quantities are made non-dimensional with reference to the side $l$ of the square section ($b=l$ in Eq. (1)).

The aerodynamic properties of the top part of the spine were determined by wind tunnel tests carried out at the end of 2012. Tests were performed in smooth flow, on a 1:6.5 rigid sectional model composed by the assemblage of aluminum plates (Fig. 28); the model had a span length 500 mm and was mounted in cross-flow configuration using the same balance, end plates and acquisition system described above. In order to explore possible Reynolds number effects, also in this case almost negligible, tests were carried out varying the wind-tunnel velocity in the range between 7.8 to 24.7 m/s. The relative angle of attack β of the wind was varied by rotating the model from –5° to +50°, with steps between 2 and 5°. Similarly to Figs. 25 and 27, Fig. 29 shows the diagrams of $c_D$, $c_L$, $c_D+c'_L$, $c'_D-c_L$, $S$ and $c_{Lrms}$ as functions of β. These quantities are made non-dimensional with reference to the side $l$ of the section ($b=l$ in Eq. (1), with $l=380$ mm in full scale, excluding the batten plates).

It is worth noting to compare the drag force of the column with the covering modules and that of an equivalent

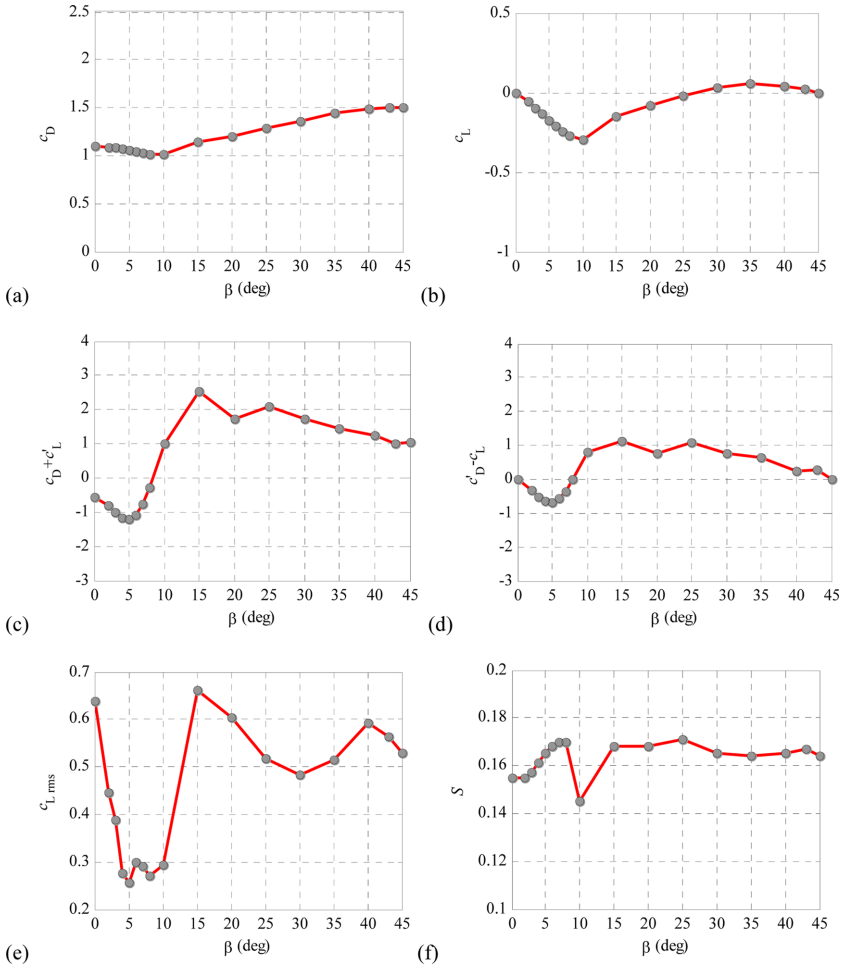



**Figure 25.** Aerodynamic parameters of the column: (a) drag coefficient; (b) lift coefficient; (c) coefficient $c_D + c'_L$; (d) coefficient $c'_D - c_L$; (e) Strouhal number; (d) rms value of the lift coefficient.

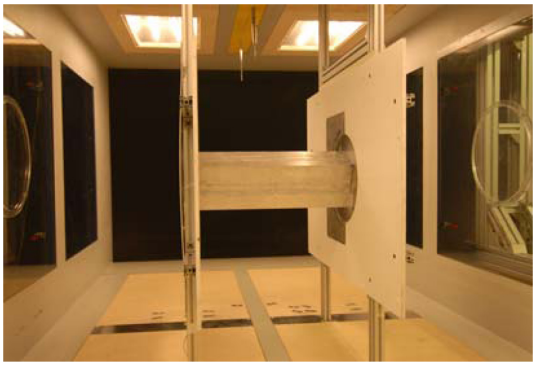


**Figure 26.** Sectional model of a square section prismatic element in the wind tunnel.

prismatic element, with square section of constant length side $l$ and exposed surface equal to that of the column ($l = 0.82 \cdot B$). In virtue of its shape variable with the height, when the wind is perpendicular to a side ($\beta = 0^o$) or diagonal ($\beta = 45^o$), the column has a drag force equal, respectively, to 62% and 83% of that of the equivalent element. So it has, in terms of the drag force, a very high aerodynamic efficiency, above all when the wind is perpendicular to its sides.

It is also worth noting to compare the parameters of the vortex wake created by the column and by a square section prismatic element. Using the definition of $S$ in Eq. (1), the vortex shedding frequency $n_s$ of the column is intermediate between the couples of the $n_{s1}$ and $n_{s2}$ values corresponding, respectively, to two prismatic elements with sides equal to the largest ($l_1 = B = 900$ mm) and to the smallest ($l_2 = B/2 = 450$ mm) size of the section of the column. Furthermore the tests demonstrate that, for any wind direction, the vortex shedding frequency of the column falls in a dispersed harmonic band, caused by a very irregular vortex wake. So the column has, also with reference to the vortex shedding, a very high aerodynamic efficiency.

Finally note the behavior of the top part of the spine. Being the angle brackets separated, the air passes through the section. Thus the drag force is reduced and the excitation due to the vortex shedding decreases to almost vanish; for $\beta = 0^o$ and $\beta = 45^o$, in particular, there is no regular shedding of vortices. On the other hand, for $\beta = 0^o$, the negative value of $c_D + c'_L$ is high. Thus the spine, free or

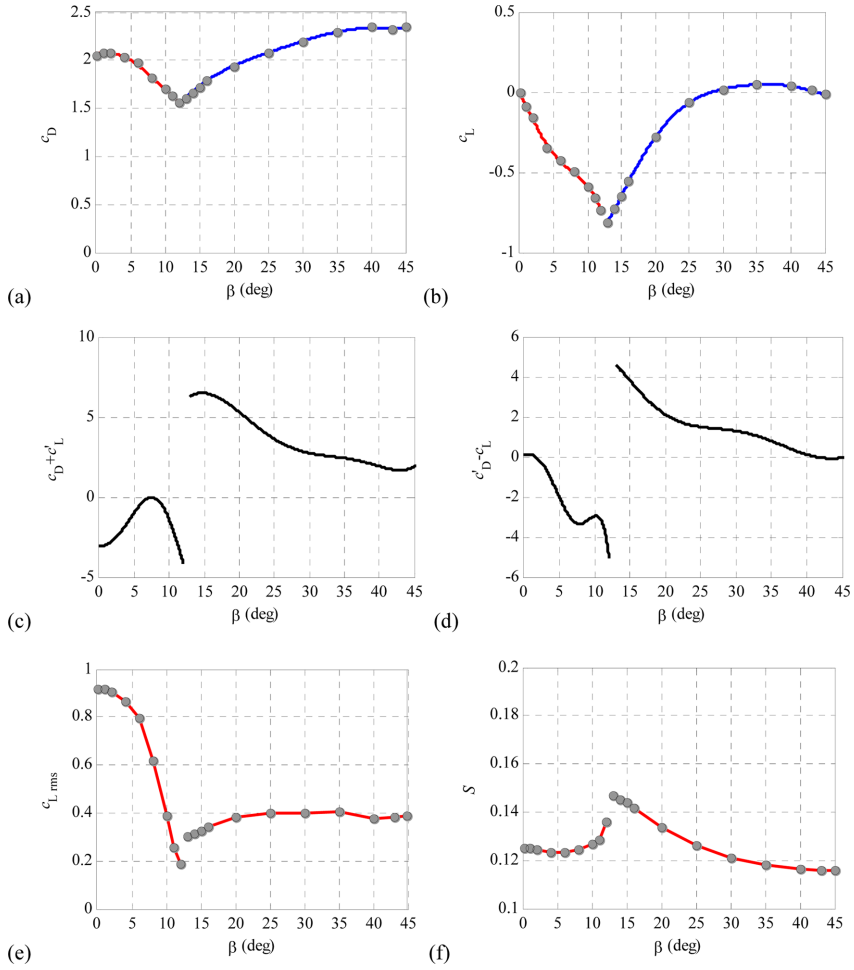



**Figura 27.** Aerodynamic parameters of the square section prismatic element: (a) drag coefficient; (b) lift coefficient; (c) coefficient $c_D + c'_L$; (d) coefficient $c'_D - c_L$; (e) Strouhal number; (d) rms value of the lift coefficient.

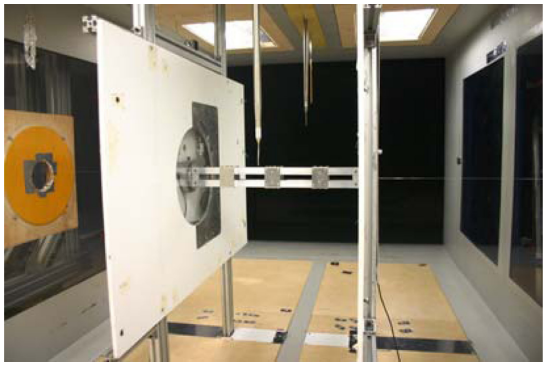


**Figure 28.** Sectional model of the top part of the spine in the wind tunnel.

wrapped, has high susceptibility to galloping.

## 7. Wind and Structural Modeling

Coherently with the Eurocode 1, the Rumanian code assigns the zone of Targu Jiù a base reference wind velocity $u_b = 25.3$ m/s (averaged over 10 minutes, at the height $z =$ 10 m, in a flat homogeneous terrain with roughness length $z_0 = 0.05$ m and return period $R = 50$ years).

The column is set in a park with mown grass, surrounded by trees and hedges (Fig. 30(a)). To the west is the center of Targu Jiù; to the north, east and south is a suburban area that degrades towards open country (Fig. 30(b)). Using the Eurocode 1 and the Rumanian code, the column is in a terrain of category II, with roughness length $z_0 = 0.05$ m. The mean wind velocity with $R = 50$ years at the top of the column, $h = 29.26$ m, is $\overline{u}(h) = 30.63$ m/s.

The actual properties of the wind at the column are estimated by means of a detailed model of the roughness length of the terrain, using the method formulated by ESDU (1993). Figure 31(a) shows the mean wind velocity profiles $\overline{u}(z)$, for 12 wind directions $\alpha$ ($\alpha = 0^o$, $30^o$, ... $330^o$; $\alpha = 0^o$ corresponds to the wind from the north, Fig. 31(b)). The same figure shows the mean wind velocity profile for $z_0 = 0.05$ m; it is greater than all the directional profiles. The maximum value of the mean wind velocity at the top of the column with $R = 50$ years is $\overline{u}(h) = 28.82$ m/s (less than the value $\overline{u}(h) = 30.63$ m/s provided by the code) and occurs for $\alpha = 120^o$.

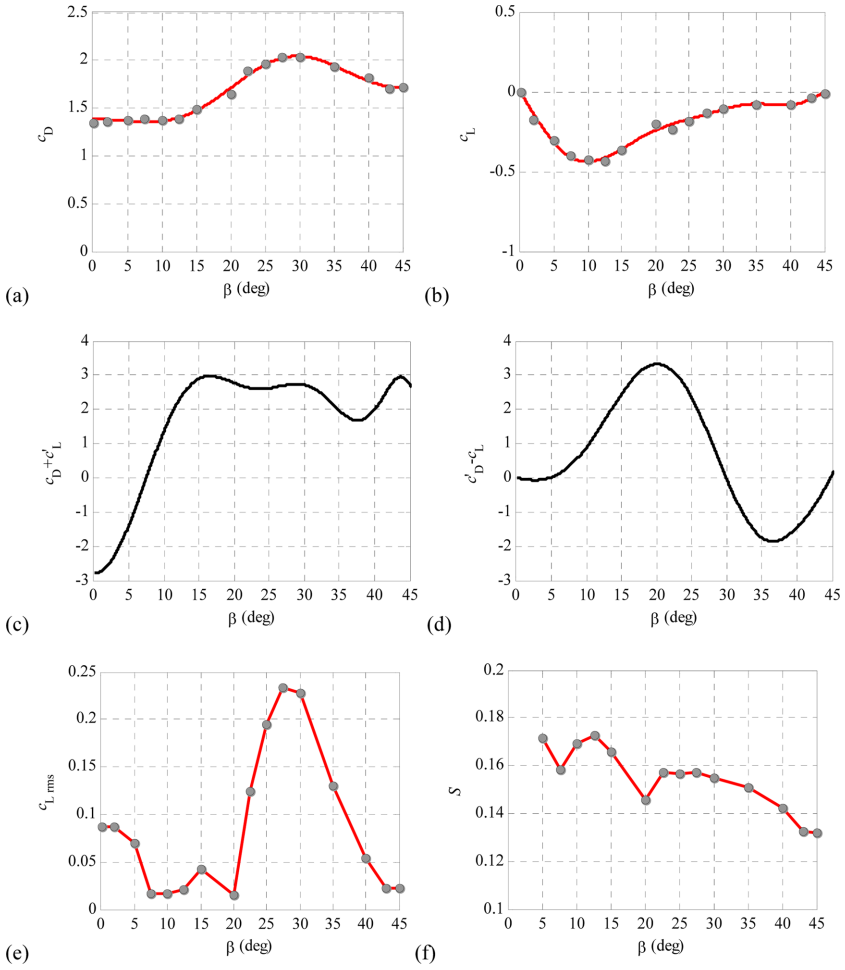



**Figura 29.** Aerodynamic parameters of the top part of the spine: (a) drag coefficient; (b) lift coefficient; (c) coefficient $c_D + c'_L$; (d) coefficient $c'_D - c_L$; (e) Strouhal number; (d) rms value of the lift coefficient.




**Figure 30.** Plan view of the site of the column: (a) park; (b) neighbourhood area.

The atmospheric turbulence is represented by the model proposed by Solari and Piccardo (2001).

The structure is schematized by two finite element models corresponding, respectively, to the column without and with the covering modules. Both these models are constituted by beam elements, vertical and superposed, with 6 degrees-of-freedom (DOF) per node. The node at the base is clamped.

The stiffness and the mass of the column without the covering modules are evaluated as a function of the geometry of the cross-section of the spine (Fig. 14). Since the inertia central ellipse is a circle with the center in the barycentre, all the couples of barycentric orthogonal axes $x$, $y$ (Fig. 24) are also principal axes of inertia. So, the flexural modes occur in couples with equal natural frequencies and modal shapes, respectively, in the planes $x$, $z$ and $y$, $z$. The calculated natural frequencies are in perfect agreement with the measured ones (Table 1).

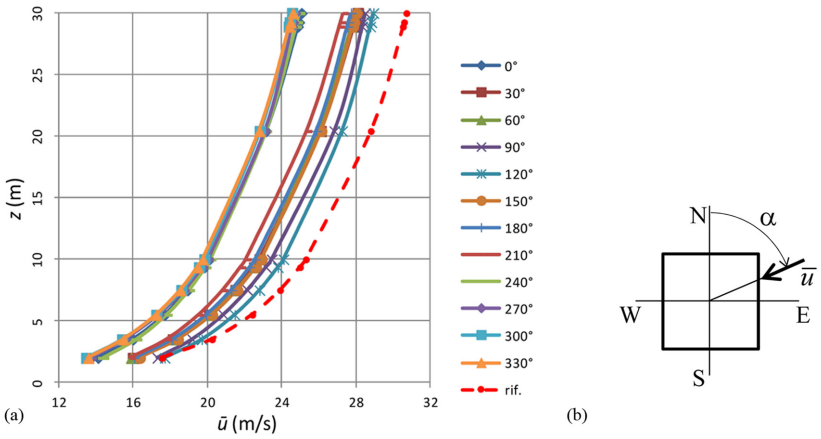



**Figure 31.** (a) Mean wind velocity profiles at the column as a function of the wind direction; the dashed line corresponds to the roughness length $z_0 = 0.05$ m (code); (b) reference system.

The mass of the complete column is determined by taking into account the contribution of the covering modules. The increment of the stiffness due to such modules is considered by attributing the steel of the spine an equivalent elasticity modulus obtained equating the numerical and measured fundamental frequency (Table 2).

The numerical results show that the first flexural modes of the column with and without the covering modules are almost coincident. The modal shapes in the planes $x$, $z$ and $y$, $z$ of the first couple of modes is well approximated by the law $\psi(z) = (z/h)^{1.75}$.

All the analyses herein carried out attribute the damping coefficients the measured values. Thus, for the spine without the covering modules $\xi_{s1} = \xi_{s2} = 0.0082$; for the column with the covering modules $\xi_{s1} = \xi_{s2} = 0.016$.

## 8. Aeroelastic Instability and Dynamic Response

The column is so slender, light and slightly damped as to be a natural candidate to the onset of aeroelastic instabilities and in particular of galloping, a form of instability corresponding to cancel the damping. It is called 1-DOF galloping when this phenomenon involves only one mode of crosswind vibrations; it is called 2 DOF galloping when it involves two modes of alongwind and crosswind vibrations, respectively; it is called multi-DOF galloping when it involves more modes of vibration. In the present case the natural frequency of the first couple of modes is so smaller than the other ones as to allow only 1-DOF and 2-DOF galloping. The first occurs when the wind blows along a symmetry axis of the cross-section ($\beta = 0^o$ and $\beta = 45^o$), decoupling the alongwind and crosswind vibrations; the second occurs in all the other cases, when the alongwind and crosswind motions are coupled. The critical galloping velocity $\overline{u}_{cr}$ is the minimum value of $\overline{u}(h)$ for which galloping occurs.

Figure 32 shows the critical galloping velocity of the column with the covering modules, as a function of the wind direction. For $\beta = 0^o$, so in the case of 1-DOF galloping, $\overline{u}_{cr} = 217$ m/s ($c_D + c'_L = -0.56$). The critical velocity reduces for small values of the angle of attack β, reaching the minimum $\overline{u}_{cr} = 95$ m/s for $\beta = 5^o$, where $c_D +$

**Table 1.** Natural frequencies of the spine (without the covering modules)

| Natural frequency | calculated | measured |
|---|---|---|
| mode $k$ | $n_k$ (Hz) | $n_k$ (Hz) |
| 1, 2 | 0.833 | 0.830 |
| 3, 4 | 3.716 | 3.735 |
| 5, 6 | 6.849 | - |

**Table 2.** Natural frequencies of the column (with the covering modules)

| Natural frequency | calculated | measured |
|---|---|---|
| mode $k$ | $n_k$ (Hz) | $n_k$ (Hz) |
| 1, 2 | 0.513 | 0.513 |
| 3, 4 | 2.519 | - |
| 5, 6 | 6.410 | - |

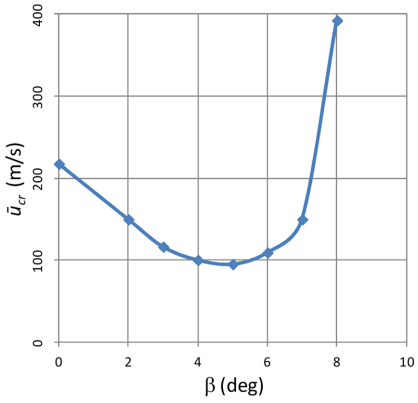



**Figure 32.** Galloping critical velocity of the spine as a function of the wind direction.

$c'_L = -1.21$ assumes its minimum value (Fig. 25(c)). For $\beta > 8^o$, where $c_D + c'_L > 0$ (Fig. 25(c)), the column is not susceptible to galloping. Anyway, again in virtue of the efficiency of its shape, the column has a so high critical velocity as to make the galloping so improbable as to be actually impossible.

The situation worsens dramatically when the spine is not covered by the modules. When its top is transparent to the wind flow, the minimum value of the critical velocity is $\overline{u}_{cr} = 20$ m/s and it occurs for $\beta = 0^o$ ($c_D + c'_L = -2.80$, Fig. 29(c)). Such value further reduces when the spine, wrapped in a plastic sheet, has a square section also in the top part. In this case, for $\beta = 0^o$, $\overline{u}_{cr} = 19$ m/s ($c_D + c'_L = -3.03$, Fig. 27(c)); for $\beta = 12^o$, $\overline{u}_{cr} = 15$ m/s ($c_D + c'_L = -4.14$, Fig. 27(c)). These values of the mean wind velocity correspond to return periods lower than 50 years; thus, without the covering modules, and even more if wrapped in a plastic sheet, the spine is exposed to a very high risk of collapse due to the galloping.

Once it is determined that the column with the covering modules has a high safety margin with respect to the galloping, while the spine without the modules is exposed to a relevant risk of collapse, one has to evaluate the dynamic response of the complete column to the forces induced by the mean wind velocity, by the atmospheric turbulence and by the vortex wake. In general, they cause both alongwind and crosswind actions. The problem simplifies when the wind is directed along a symmetry axis of the cross-section, namely for $\beta = 0^o$ or $\beta = 45^o$. In this situation the mean wind velocity determines an alongwind mean static force. The longitudinal, $u'$, and the lateral, $v'$, turbulence components cause alongwind and crosswind actions, respectively. The vortex shedding produces crosswind actions much larger than the alongwind ones. Using the method proposed by Piccardo and Solari (2002), a wind loading effect is given by the relationship:

$$e(t) = \overline{e} + e'_Q(t) + e'_R(t) \tag{2}$$

where $\overline{e}$, $e'_Q$ and $e'_R$ are, respectively, the mean value, the quasi-static part and the resonant part of $e$. Based on Eq. (2) the mean value of the distribution of the maximum of $e$, referred to as the maximum value, is given by:

$$\overline{e}_{max} = \overline{e} + g_e \sqrt{\sigma^2_{Qe} + \sigma^2_{Re}} \tag{3}$$

where $g_e$ is the peak coefficient of $e$; $\sigma^2_{Qe}$ and $\sigma^2_{Re}$ are the variances of $e'_Q$ and $e'_R$. The evaluation of $g_e$, $\sigma^2_{Qe}$ and $\sigma^2_{Re}$ generally requires a numerical approach. Closed form expressions of these quantities are given by Piccardo and Solari (2002) under the conditions that the dynamic response is dominated by the first couple of modes of vibration, and the effect $e$ depends only on the alongwind or crosswind motions. In the present case the first condition is widely satisfied; the second is satisfied for $\beta = 0^o$ and $\beta = 45^o$ (Fig. 24).

Figure 33 shows the diagrams of the maximum values of the two components of the displacement at the top, $x(h)$ and $y(h)$ (Fig. 33(a), (b)), and of the bending moment at the base, $M_x(0)$ and $M_y(0)$ (Fig. 33(c), (d)) as a function of $\overline{u}(h)$, for $\alpha = 90^o$ ($\beta = 0^o$, Fig. 33(a), (c)) and $\alpha = 135^o$ ($\beta = 45^o$, Fig. 33(b), (d)). Excluding the low mean wind velocity values, where the vortex-excited response occurs, the wind-induced effects along $x$, due to the mean wind velocity and the longitudinal turbulence component, are always much greater than those along $y$, due to the lateral turbulence component and the vortex shedding.

The diagrams of the crosswind response point out the critical condition that occurs for $\overline{u}(h) = 2.96$ m/s, when the vortex shedding is resonant with the first mode of crosswind vibration; the very high value of the Scruton number ($Sc = 119$) prevents the lock-in phenomenon in the nonlinear range and strongly limits the response. As far as concerns the resonance of the vortex shedding with the second mode of crosswind vibration, which occurs for $\overline{u}(h) = 14.55$ m/s, it does not produce any relevant effect.

The resistance verification at the Ultimate Limit States, carried out in accordance with the Eurocode 3, show that the column has, already in its original configuration, large safety margins for any section and any wind direction. This fact points out the groundlessness of all restoration carried out in order to increase the resistance of some sections on the basis of reasons inspired by local alleged weaknesses of the spine with respect to the wind.

## 9. Wind-induced Fatigue

It is well known that the wind-induced fatigue is a severe snare for steel structures, especially for those which are slender, flexible, light and low-damped. The Endless Column therefore requires a detailed assessment of its fatigue life. This is given by the relationship:

$$T_f = \frac{1}{\overline{D}(1)} \tag{4}$$

where $T_f$ is expressed in years and $\overline{D}(1)$ is the mean annual value of the fatigue-induced damage. This quantity is determined on the basis of two hypotheses:

1) the distribution function of the reference mean wind velocity is given by the hybrid Weibull model:

$$F(\overline{u}) = 1 - (1 - F_0)\exp\left[-\left(\frac{\overline{u}}{c}\right)^k\right] \quad (\overline{u} \geq 0) \tag{5}$$

where $F_0$ is the probability of occurrence of the wind calms, $k$ and $c$ are the shape and scale parameters, respectively;

2) coherently with the Eurocode 3 (2005b), the S-N fatigue curve of a structural detail is given by:

$$N \to \infty \quad \text{for} \quad \Delta \leq \Delta_L$$

$$N = \frac{a_2}{\Delta^{m_2}} \quad \text{for} \quad \Delta_L \leq \Delta \leq \Delta_D \tag{6}$$

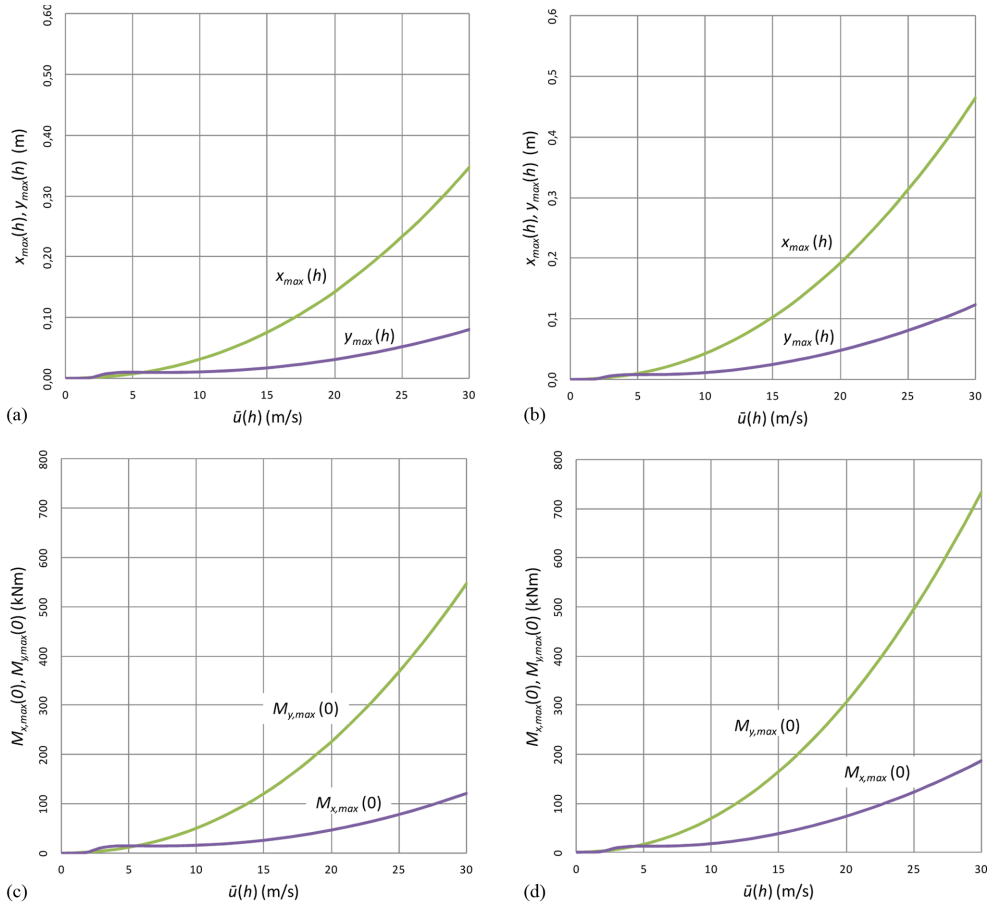



**Figure 33.** Maximum values of the top displacements (a,b) and of the base bending moments (c,d) of the column when the wind is perpendicular to a side ($\beta = 0^o$) (a,c) and diagonal ($\beta = 45^o$) (b,d).

$$N = \frac{a_1}{\Delta^{m_1}} \quad \text{for} \quad \Delta \geq \Delta_D$$

where $\Delta$ is the stress range, $N$ is the number of cycles with range $\Delta$ that causes the fatigue collapse, $\Delta_D$ and $\Delta_L$ are the values of $\Delta$ that correspond, respectively, to $N = N_D = 5\times10^6$ and $N = N_L = 10^8$. The fatigue curve is identified by the detail category $\Delta_C$, namely the value of $\Delta$ corresponding to $N = N_C = 2\times10^6$.

The mean value of the annual fatigue-induced damage is evaluated in directional form as the sum of the mean annual values of the damage associated with the different wind directions. It follows that:

$$\overline{D}(1) = \sum_{j=1}^{S} \overline{D}_j(1) \tag{7}$$

where $S$ is the number of the considered directional sectors, $\overline{D}_j(1)$ is the value of the mean annual value of the damage caused by the wind blowing from the $j$-th sector. It is evaluated by means of the method proposed by Repetto and Solari (2009, 2012) considering only the stress state caused by the wind in the alongwind direction, thus neglecting the contributions of the vortex shedding and of the lateral turbulence component. In this case such hypothesis is justified by at least two reasons: 1) the internal forces in the alongwind direction are much larger than those in the crosswind direction (Fig. 33); 2) since the internal forces in the alongwind direction are not correlated with the crosswind ones, the maximum values of the respective stresses are not contemporary.

The analyses, still preliminary, are carried out on the basis of several conventional choices: 1) since no reliable data of the wind climate of Targu Jiu is available, as a first approximation it is assumed that the base reference velocity and its frequency of occurrence are the same for any wind direction; 2) three possible values are attributed to the shape parameter of the Weibull model (Eq. 5), $k$ = 1,4 1.8, 2.2; 3) three reasonable values are attributed to the detail category of the spine at different heights, $\Delta_C$ = 40, 45, 50 N/mm$^2$. Therefore, the following results have to be dealt with as indicative.

Figure 34 shows the diagrams of the maximum value of the normal stress $\sigma$ induced by the wind in a spine corner, for $S = 8$ directional sectors associated with the 4 symmetry axes of the cross-section. The analyses are referred to the column after the restoration. The maximum stresses occur at heights 0.56 and 9.36 m, when the wind is diagonal. It is worth noting that the section at 9.36 m height has been

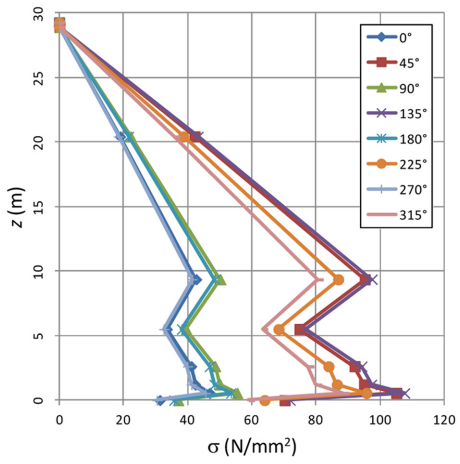



**Figure 34.** Maximum value of the normal stress induced by the wind in a corner of the spine, as a function of the wind direction α.

never considered as critical.

Figure 35 shows the diagrams of the fatigue life $T_f$ of the section of the spine at different heights, on varying the parameters $k$ and $\Delta_C$. It is apparent that the fatigue life is extremely sensitive to the values of both these parameters: it increases when the detail category $\Delta_C$ increases; it decreases when the $k$ value increases. In the intermediate case, for $k = 1.8$ and $\Delta_C = 45$ N/mm$^2$, $T_f$ takes values quite reassuring but not definitely high: $T_f = 111$ and 159 years at heights 0.56 and 9.36 m, respectively. It is very high for $k = 1.4$ and $\Delta_C = 50$ N/mm$^2$: $T_f = 422$ and 588 years at heights 0.56 and 9.36 m, respectively. It is insufficient for $k = 2.2$ and $\Delta_C = 40$ N/mm$^2$: $T_f = 25$ and 36 years at heights 0.56 and 9.36 m, respectively; this result is in contrast with the fact that before the restoration the column has lived for about 60 years without exhibiting relevant fatigue damage.

It is worth noting that the connection with the silicone of the covering modules has deprived the column of a source of dissipation by friction likely relevant. Figure 36, analogous to Fig. 35, shows the values of $T_f$ for a structural damping coefficient $\xi_s = 0.032$, double of that measured after the restoration. In this hypothetical case the fatigue life substantially increases.

There is no evidence to draw firm conclusions nor to advance any theory. However, there is a minimum doubt that the column has spent its first 60 years of life without exhibiting apparent fatigue damage also in virtue of the damping provided by the lack of connection among the modules. Limitedly to the available data, it is not entirely clear that the new configuration of the column ensures an equal future survival in the absence of damage. This topic deserves to be deepened with more specific evaluations based on reliable data.

## 10. Conclusions and Prospects

The study of the actions and effects of the wind on the

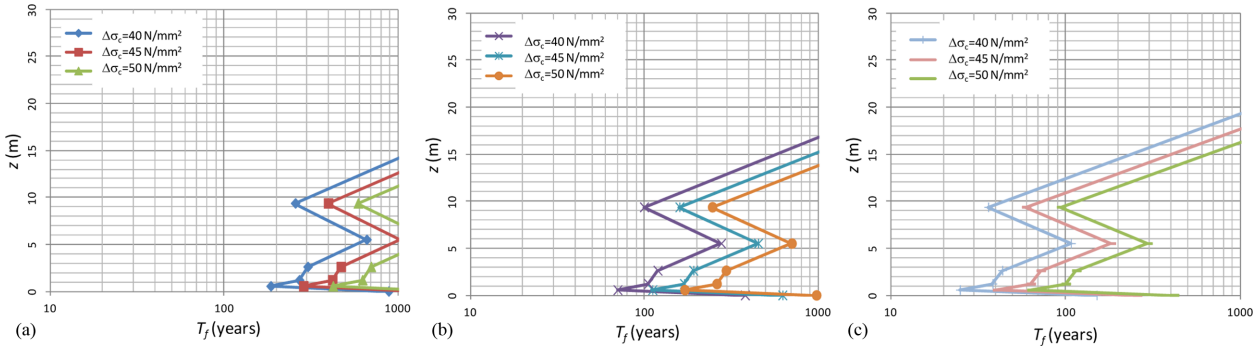



**Figure 35.** Fatigue life of the cross-sections of the spine ($\xi_s = 0.016$): (a) $k = 1.4$; (b) $k = 1.8$; (c) $k = 2.2$.

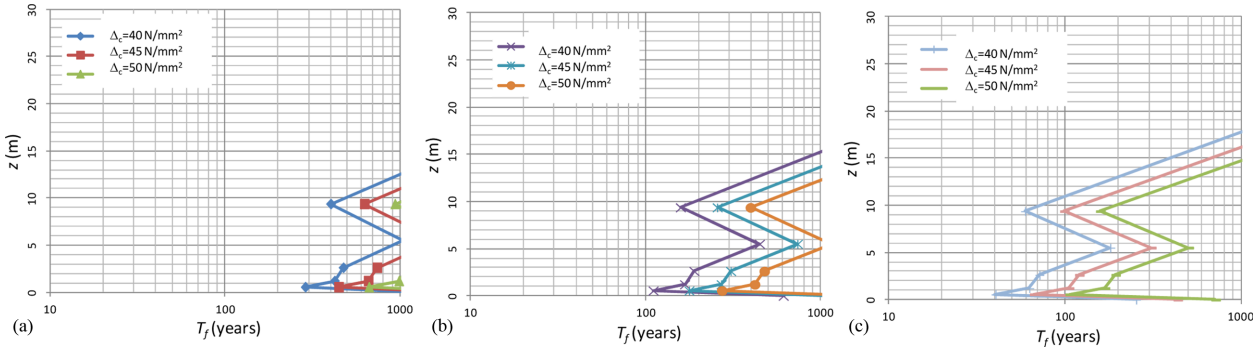



**Figure 36.** Fatigue life of the cross-sections of the spine ($\xi_s = 0.032$): (a) $k = 1.4$; (b) $k = 1.8$; (c) $k = 2.2$.




**Figure 37.** (a) Taipei 101, Taiwan; (b) World Financial Center, Shanghai; (c) Infinity Tower, Dubai; (d) Burj Khalifa, Dubai; (e) Glasgow Science Centre Tower, Ireland.

Endless Column, begun in Genova in 2001 and still in progress, shows that the column is not only a milestone of art and engineering, but it truly translates the principle of perfect aerodynamic conception and the maximum synthesis between form and structure. Despite being endowed with such an elevated slenderness as to potentially make it prey to the wind, thanks to its undulated edges the column has a modest drag, it creates a chaotic vortex wake and therefore being incapable of inducing violent crosswind actions, it eludes every form of aeroelastic instability. The distribution of the structural material admirably takes on the risks to which it is exposed. The construction details create elevated dissipative resources and guarantee maximum durability and robustness to the column. All is balanced in an extraordinarily equilibrated way. Many studies developed downstream of these evaluations have regularly confirmed these assessments (Gabbai, 2007; Dragomirescu et al., 2009).

Not by chance the numerous interventions performed over the years to modify the column have regularly worsened the set up and exalted its peculiarities. The towing applied in 1953 with the tractor damaged the spine and the foundation highlighting the robustness of the structure. The closing of the ventilation hole in 1990 accelerated the decay. The removal of the covering modules and the abandoning of the spine to bad weather, in 1996, exposed the work to an elevated risk of collapse and deteriorated the material. The wrapping of the spine with a plastic sheet increased the risk of collapse and encouraged corrosion. The reinforcement of the spine in 2002 was pointless. The adding of silicone to the joints between the covering modules deprived the column of a source of dissipation such as to highlight the opportunity of new in-depth examinations with regard to fatigue.

Today the Endless Column is a point of reference and an icon for all the works, more and more numerous, in which the architect and the engineer find a meeting point and symbiosis in integrated aerodynamic design, a new vision of constructions where the shape is the interface between stylistic demands and the process of optimization of the structural performance (Irwin, 2009). Some skyscrapers, particularly Taipei 101 (Fig. 37(a)), are expressly inspired by the column adopting a configuration for modules overlapping by varying sections that reduces the drag force and breaks up the vortex wake. Others make use of sections of variable (World Financial Centre, Shanghai, Fig. 37(b)), rotated (Infinity Tower, Dubai, Fig. 37(c)) or tapered (Burj Khalifa, Dubai, Fig. 37(d)) shape that mitigate the wind actions by virtue of the principles used firstly by the column and widely debated in the recent technical literature of wind engineering (Tamura et al., 2010).

The column is also the emblem of the works that use aerodynamic fairings to adapt their own form to the action of the wind; among these Glasgow Science Centre Tower (Fig. 37(e)) stands out, a stele with winged form that rotates in the wind to reduce the drag force, and in general bridges (Great Belt East Bridge, Denmark; Bronx Whitestone Bridge, U.S.) and cables (Tatara Bridge, Japan; Sutong Bridge, China) endowed ever more often with outlines and covering profiles to contrast aerodynamic phenomena most prejudicial to stability.

Brâncuşi and Gorjan were aware of having created a masterpiece of art and engineering. Nevertheless, it is difficult to understand to what extent they realized the aerodynamic implications of their project, the meaning of the form that they had conceived, the inspiring principle of the aerodynamic fairing entrusted to the covering modules and the concept of the shape control. A sentence from Constantin Brâncuşi allows us to imply that his genius had at least partly realized what would be recognized of him

in the future: "Nature creates the plants that grow from the earth, strong and straight like my column. Its shape is the same, from the earth toward the sky. It does not need a pedestal to support it. It is firmly anchored to the ground because everything must be born from the ground. The wind does not move it, it supports itself with its own strength. It is immovable".

## References


Andronescu, S. C. and Melczer, M. C. (2004). "Brâncuşi's attempt to infinity." American Institute for Writing Research, New York, U.S.A., The "Endless Column" Museum, City of Petrosani, Romania.

Brezianu, B. (1999). Brâncuşi in Romania. Editura All, Bucharest, Romania.

Carassale, L., Freda, A., Marré Brunenghi, M., Piccardo, G. and Solari, G. (2012). "Experimental investigation on the aerodynamic behaviour of square cylinders with rounded corners." *Proc. 7th Int. Coll. on Bluff Body Aerodynamics and Applications*, Shanghai, China.

Crisan, M. and Dogariu, L. (2000). Endless Column by Constantin Brâncuşi Tirgu Jiu - Romania. Structural restoration design. Structural diagnosis and treatment strategy, Union of Plastic Artists, Bucharest.

Crisan, R. (2000). Endless Column by Constantin Brâncuşi, Tirgu Jiu, Romania - Restoration Guidelines. Union of Plastic Artists, Bucharest.

Croci, G., Forrieres, C. and Bonci, A. (1998). Mission à Bucharest et Tirgu Jiu (Roumanie) - Rapport technique sur la "Colonne Sans Fin" de Constantin Brâncuşi, UNESCO.

Dragomirescu, E., Yamada, H. and Katsuchi, H. (2009). "Experimental investigation of the aerodynamic stability of the "Endless Column", Romania." *Journal of Wind Engineering and Industrial Aerodynamics*, 97, pp. 475~484.

Engineering Sciences Data Unit (1993). Computer program for wind speeds and turbulence properties: flat or hill sites in terrain with roughness changes, ESDU Item 92032, London, U.K.

Eurocode 1 (2004). Actions on structures - General actions - Part 1-4: Wind actions.

Eurocode 3 (2005a). Design of steel structures - Part 1-1: General rules and rules for buildings.

Eurocode 3 (2005b). Design of steel structures - Part 1-9: Fatigue.

Gabbai, R. D. (2007). "On the aeroelastic indifference of Brâncuşi's Endless Column." *Proc. 12th Int. Conf. on Wind Engineering, Cairns*, pp. 1111~1118.

Georgescu, E. S., Stancu, M. and Bratu, F. (1986). "The theoretical and experimental dynamic analysis of the Romanian, European and universal art monument: The Endless Column of Constantin Brâncuşi sculptor, erected at Targu-Jiu, Romania." *Proc. 8th European Conf. on Earthquake Engineering*, Lisbon, Portugal.

Georgescu Gorjan, S. (2001). Istoria Colonae Infinite. Editura Destin, Romania.

Irwin, P. A. (2009). "Wind engineering challenges of the new generation of super-tall buildings." *Journal of Wind Engineering and Industrial Aerodynamics*, 97, pp. 328~334.

Lungu, D. (2000). Wind action on Brâncuşi Endless Column at Tg.Jiu, Romania, according to the wind loading codes from European Union, USA and Romania. Technical Report, Union of Plastic Artists, Bucharest.

Lungu, D., Solari, G., Vacareanu, R., Aldea, A., Arion, C. and Demetriu, S. (2005). "Ambient vibration measurements and along-wind response of the Brâncuşi Endless Column, Romania." *Proc. 4th European & African Conf. on Wind Engineering*, Prague, Czech Republic.

Milligan, S. E. and Tully, J. (1995). "Endless problem." ARTnews, October, pp. 126~130.

Parigoris, A. (2002). "Endless Column restored." *Sculpture*, 21(1).

Piccardo G. and Solari G. (2002). "3-D gust effect factor for slender vertical structures." *Probabilistic Engineering Mechanics*, 17, pp. 143~155.

Repetto, M. P. and Solari, G. (2009). "Closed form solution of the alongwind-induced fatigue damage of structures." *Engineering Structures*, 31, pp. 2414~2425.

Repetto, M. P. and Solari, G. (2012). "Closed form prediction of the alongwind-induced fatigue of structures." *Journal of Structural Engineering*, ASCE, 138(9), pp. 1149~1160.

Solari, G., Lungu, D., Bartoli, G., Righi, M., Vacareanu, R. and Villa, A. (2002). "Brâncuşi Endless Column, Romania: dynamic response and reliability under wind loading." *Proc. 2nd Int. Symp. on Advances in Wind & Structures*, Busan, Korea, pp. 79~86.

Solari G. and Piccardo G. (2001). "Probabilistic 3-D turbulence modelling for gust buffeting of structures." *Probabilistic Engineering Mechanics*, 16, pp. 73~86.

Tabart, M. (1995). Brâncuşi: L'inventeur de la sculpture moderne. Gallimard, Centre Georges Pompidou.

Tamura, Y., Tanaka, H., Ohtake, K., Nakai, M. and Kim, Y. C. (2010). "Aerodynamic characteristics of tall building models with various unconventional configurations." *Proc. 2010 Structures Congress*, Orlando, Florida, pp. 3104~3112.

Treatment recommendations for the Brâncuşi Monumental Ensemble. (1999). Report of Technical Symposium. Targu Jiu e Bucharest, 2-4 June 1999, World Monuments Fund, World Bank, Romanian Ministry of Culture, Constantin Brâncuşi International Foundations.