Abstract. The paper presents the construction and architectural characteristics of the most spectacular twisted forms of high-rise buildings that have hotel, office, residential and public functions. The stiffness of the bearing structure is a superior criterion in the shaping of such buildings and its value lies in the size of permissible vertical deflection. Limitation of the vertical deflection of a high-rise building is not only aimed at preventing and minimizing the adverse P-delta effects on the structure of the building. The stiffness of a tall building can also be considered as an indirect indicator of its susceptibility to dynamic influences. This impact depends on the strength of the wind and on the aerodynamic properties of the building. The value of the wind load increases with the height of the building. High spatial rigidity reduces the amount of acceleration associated with the horizontal displacements of a structure and also increases the natural vibration frequency, which for low values can be dangerous for construction. The structure can fall into resonance at critical wind speeds, which generates both high stresses and vertical deflection. The aerodynamic twisted shape has the advantage of disturbing the form of the impact of wind around the building to effectively reduce wind excitation.

1. Introduction
One of the biggest challenges for engineers when designing modern high buildings is the impact of wind. It has a dynamic character and its strength depends on the aerodynamic properties of the building and strength of the wind [1]. Analysis of the aerodynamic system of buildings concerns variable phenomena, which are dependent on many unpredictable factors, Fig. 1. The structure of air swirling around a building, as a result of air mass collision with the building’s form, is very complex and not fully explained theoretically. Therefore, traditional calculation methods that are, sufficient for static load testing are not an effective tool in this regard. Experimental and advanced computer simulations are required. For buildings with complex shapes, and because there are no standard procedures for this type of construction, research is performed in an aerodynamic tunnel. Rigid reinforced concrete cores are constructed for the transfer of horizontal loads and to prevent buildings from swaying. Apart from swaying, the wind has a significant impact on a building when the vortex shedding frequency approaches its natural vibration frequency. If the vortex causes a building's vibration to be equal to its resonant frequency, enormous forces are generated which in turn could cause a catastrophe. To prevent this, an aerodynamic shape of the building or a very differentiated facade is designed in order stop the overlapping of vortexes. Another way to counteract the effects of the wind is to adjust the tuned mass damper (vibration absorber). When a building starts to sway in one direction, the pendulum at the same frequency tilts to the opposite side. This suppresses vibration
and thus reduces the deviation of the building. In other types of tuned mass dampers, there are hydraulic elements that convert kinetic energy into heat. The vibration absorbers are not only placed in the upper part of the building or on the roof, but also in the elements of the structure, e.g. in the steel truss. After first paragraph, other paragraphs are indented as you can see in this paragraph. After Introduction, divide your article into clearly defined and numbered sections.

**Figure 1.** Scheme of the adoption of load areas of high-rise buildings: a) along the height, b) on the lateral wall

In order not to occupy the valuable floor space of a skyscraper, other solutions to the problem of vibration have emerged. Christopoulos and Montgomery created a system that distributes damping throughout a building using a viscoelastic viscous material that is bonded to steel [2]. Their damper absorbs the vibrations caused by wind or earthquakes and concentrates damage on the individual parts of the damper that are easy to replace. The carrying out of tests in aerodynamic tunnels in the design phase of high-rise buildings is recommended.

Such tunnels are designed to simulate changes in wind speed by increasing the height of the test model. The model is subjected to wind load at every possible angle. Smoke is often used to depict the effect of the wind. Sensors mounted at different points in the model read data, and after being imported to a computer, a detailed analysis is provided. An aerodynamic twisted shape has the advantage of disturbing the form of wind impact around a building to effectively reduce wind excitation. Various aerodynamic building modifications can take the form of [3]:

- a conical cross-section and retraction in the building line Fig. 2a,
- a helical shape Fig. 2b,
- adding holes Fig. 2c,
- corner modification Fig. 2d.
The paper focuses on examples of aerodynamic twisted forms of tall buildings.

2. Twisted buildings

In modern architecture, several groups within the category of twisted buildings can be distinguished, Fig. 3. Buildings in the form of twisted solids, where the next floors are built up by the repetition of the ground floor plan with the rotation of the vertical axes that is normally located in the center of the floor plan belong to the "twister" category. Buildings with an orthogonal core and with one or two twisted towers form the "tordo" category. This is a transformed volume with at least one corner that is moved out from the orthogonal structural grid. The floors are basically repeated in the vertical direction with interior walls and columns aligned. In contrast, when the floors are offset upwards along a 2D or 3D curve and when the rotation is additionally added to the external shape of the building’s structure, the building belongs to the "sliding twister" category. The last group includes twisted shaped buildings with a spiral rotation axis, known as the “helical twister” category [4].

The idea of a twisted building is the result of searching for an architectural form that would both stand out from its surroundings, and also withstand the dynamic impact of the wind better than a polyhedral solid [5] – [7]. The use of twisted forms for tall buildings has recently become an increasingly common architectural phenomenon. The precursor of this type of construction is Santiago Calatrava, who designed the world’s first twisted building in Malmo, Sweden. Spectacular examples of twisted tall buildings are the Al Bidda Tower in Doha, the Cayan Tower in Dubai, the Evolution Tower in Moscow, the Gakuen Spiral Tower in Nagoya, the Shanghai Tower (the tallest building in the world), Absolute Towers D and E in Mississauga. All these buildings have hotel, office, residential and public functions. It is also worth mentioning the Agora Garden Tower, currently being built in the capital of Taiwan. It is a residential building and its shape resembles a double helix of DNA with an amazing vegetation waterfall created by balconies full of vegetation, fruit trees, and vegetable gardens.

Although there are many constructional systems for tall buildings with simple forms, only a few of them can be used for twisted forms due to their complex geometry [8] – [9]. Structural systems of existing twisted buildings are usually mega-core systems with a cylinder shape concrete core, which is sometimes surrounded by internal columns arranged concentrically (Evolution Tower) or into rows (Cayan Tower) or braces that are connected to these columns in a mesh network, that forms ab inner truss tube (Mode Gakuen Spiral Towers). Another hybrid construction system consists of a mega-core, an outer steel mega-frame and outrigger steel trusses (Shanghai Tower). A peripheral structure of the diagrid system (Al Bidda Tower) is also often used in twisted buildings. In addition to these complex systems, a traditional shear wall system (Absolute Towers) is also used in order to achieve complex geometries.
3. Examples of twisted tall buildings

3.1. The Al Bidda Tower (Doha, Qatar)

The Al Bidda Tower is an office skyscraper with reinforced concrete and steel structure. The building is 197 m height and contains 44 floors above ground and 1 below. In addition, a separate eight-floors car park adjoins the building. Al Bidda Tower was designed by the architectural studio GHD Global. The building is located in an architecturally developing area around the main street Al Corniche. It was built on a plan of a convex triangle with two risalits on each side. The entrance to the building is located at ground level. The external façade is made as a structural one and consists of a curtain wall in the form of triangles forming a diagrid and facings with separated glass. During the day, multi-layered reflective glass reflects sunlight in different directions and internal light at night. The result is a shiny facade similar to a mirror.

The Al Bidda Tower is twisted by an angle of 60 degrees through its height, Fig. 4. The construction of Al Bidda Tower consists of a circular reinforced concrete core and post-tensioned concrete floor slabs mounted to the 30th floor. The support for floor slabs consists of radially arranged beams between the external columns and the core as well as peripheral edge beams spanning between the columns. The core of the building has a thickness of 50 centimeters to a level of 24 floors above which is thinned to 40 centimeters. There are 9 main external concrete columns of varying cross-section that slope with the twist of the building and also a diagrid of steel bracing attached to the external perimeter. The columns with a circular cross-section have a diameter of 1.4 m, whereas the rectangular cross-section is 1 m x 1.7 m. Above the 30th storey, the floor beams and external columns
become steel supporting composite concrete floor slabs. There is a steel construction of diagonal bracing with round cross-sections on the entire height of the building and around the perimeter. Because of the building's twist to maintain stability, this structure must be properly balanced. The dimensions and wall thicknesses of the bracing vary with the height of the building. The braces are connected to either the perimeter concrete beams or to columns by pinned connections. Lateral loads are taken by the core and the outer steel diagonal bracing system. The torsional loads caused by inclined columns, as well as the lateral loads, are transmitted by the external bracing and the core, with the floor slabs acting as diaphragms. The building is supported on a stiff raft slab that cooperates with bored concrete piles.

3.2. The Evolution Tower (Moscow, Russia)

The Evolution Tower is an office skyscraper with reinforced concrete structure. The building is 246 m height and contains 55 floors above ground and 3 under-ground. Design of skyscraper was made by Kettle Collectives, Gorproject and RMJM studios. The building is located on the Presnenskaya Embankment of Moskva river, in the Moscow International Business Center. The evolution tower is designed on a square plan with a central core in the circle form. The design concept of the Evolution Tower is based on the symbolic evolutionary spiral of a white ribbon wrapped over a roof in the form of a 90 degree twisted infinity symbol, Fig. 5. The innovative design is based on the principles of twisted square floor slabs with a vertical reinforced concrete frame supported by a central core and eight columns in an octagonal arrangement. It has continuous beams and four spiraling columns in the corners. All floors are constantly twisted by a fixed angle of 3 degrees and are located around the central core of the building in such a way that the building is twisted in a clockwise direction from the
base to the top by an angle about 135 degrees. The engineering challenge for this venture was the need to make 52 different floor slab layouts. The proposed structural design with its cantilevered concrete continuous beams and cantilevered floor slabs are simple, effective and economical.

The double curved building envelope is obtained by applying cold bending reflective glass units. The Curtain wall uses flat, double glass elements in an aluminum frame to avoid the visual effect of "stepping" in the building’s geometry. The facade is distinguished by vertical and horizontal divisions. Vertical divisions create rectangular windows with floor height connecting with horizontal windows with the height of the slab floors between storeys.

The top of the skyscraper is two twisted steel arches with a span of 41 m and 4 smaller arched supports beneath the steel ribbon stripes. 12 concrete columns and the central core are supported by a 3.5 m thick raft over piled foundations [10].

3.3. The Cayan Tower (Dubai, UAE)
The Cayan Tower is a residential skyscraper with reinforced concrete structure. The building is 306 m height and contains 73 floors above ground and 5 under-ground. A 5-storey building with a swimming pool and terrace adjoins the main building. Cayan Tower was designed by SOM architectural group and is located in Dubai Marina, the world’s most exclusive waterfront. The building is built on chevron-shaped hexagon plan with the central circular core. Its form is inspired by the structure of human DNA with a spiral shape twisted 90 degrees over its height, Fig. 6. Each floor is twisted in a clockwise direction by an angle of 1,2 degrees relative to the floor below. The façade has glass and aluminium curtain wall system with standardized, rectangular silver painted panels with one-storey-high. Elevation has vertical and horizontal divisions. Cornices create horizontal divisions, while
vertical divisions are accentuated with rectangular windows and openwork façade panels. By reversing the windows and forwarding the openwork panels, effect of the concave-convex façade was obtained, in which the balconies were hidden.

The construction system of the tower is a high-strength superstructure of reinforced concrete columns. The stepped columns transfer their load through a concrete floor slab. The perimeter columns lean forward or backward by an angle of 10 degrees according to the offset of floor slabs that are above or below. The width, angle, and spacing of columns looks the same from floor to floor, even as the floors themselves slightly shift, as they progress higher around a quarter circle. The lateral load resisting construction system is a combination of reinforced concrete perimeter columns, spandrel beams and the core. The tower has a circular central core formed by a wall connected at each floor by two-way spanning reinforced concrete slabs acting as a diaphragm. The building is set upon a 3 m thick reinforced concrete mat foundation, which is supported by 99 reinforced concrete piles with a diameter of 1.2 m.

![Figure 6. The Cayan Tower - Plan and cross-section](image)

### 3.4. The Mode Gakuen Spiral Towers

The Mode Gakuen Spiral Towers is educational high-rise building with steel structure. The building is 170 m and contains 38 floors above and 3 below ground level, Fig. 7. The building was designed by Nikken Sekkei studio. Mode Gakuen Spiral Towers is located on a busy main street of Nagoya City in front of Nagoya Station. The building houses three vocational schools; Mode-Gakuen for fashion, HAL for information technology and design, and ISEN for medicine and welfare. The building is built on an elliptical plan with three niches with a central core in the ellipse form. The project consists of three spiral wings that are, radially arranged in relation to each other. The entrance to the building is
located at ground level. The central element of the facade has horizontal divisions accentuated with balconies and vertical ones with rectangular windows. The outer surface is made of a steel diagrid with triangular windows. The façade is distinguished by triangular windows and horizontal balcony lines.

The planar configuration of each floor changes with the height. 12 straight columns are arranged around the oval core and braces are connected to these columns in a mesh network that forms an inner truss tube. The truss tube is made of concrete-filled steel tubular columns with constructional braces fixed around the base. The columns act as a central pillar supporting the three slightly tapering wings of the building. This tubular structure is very strong and rigid with regard to the horizontal and twisting forces that are generated by earthquakes and high winds. In this type of tower building, there are considerable bending deformations and a high level of axial forces affecting the outer columns, which results in greater deformation in the upper part of the building. The construction of the building in the form of an inner truss tube and two vibration damping systems ensure high resistance to seismic actions. Vibration – damping columns efficiently absorb seismic energy by means of viscosity dampers, which are installed at 26 points on the periphery. There is also a mass damper located on the rooftop. Double-glazed windows and airflow windows are used to reduce heat loads around the perimeter zone. The foundations combine a thick raft slab and cast concrete piles.

![Figure 7. The Mode Gakuen Spiral Towers - Plan and cross-section](image)

3.5. The Shanghai Tower

The Shanghai Tower is multi-function skyscraper with a reinforced concrete and steel structure. The building is designed by Gensler studio. The Shanghai Tower is 632 m height and contains 128 above
ground floors and 5 under-ground. The skyscraper is located in the Pudong district of Shanghai in the immediate vicinity of Jin Mao Tower and SWFC. The building is designed on a convex equilateral triangle with a central core on a cross plan with a variable form. Two tangential curves offset at 60 degrees were used to create an outer, transparent glass surface. The outer surface of curtain wall connects to the inner every 13 floors and is accentuated by cornices with a height of 2 storeys. The building rises from ground level only in part of the plan and connects with the vestibule. The façade is distinguished by horizontal divisions.

The Shanghai Tower has tapering shape and consistently rounded corners, turning 120 degrees over its height, Fig. 8. The tower structure is divided into 9 vertical cylindrical zones ranging from 12 to 15 floors. The horizontal and vertical resistance is provided by the inner cylindrical tower. The primary lateral system consists of three parts: a concrete composite core, an outer steel mega frame (super columns and double belt trusses) and steel outrigger trusses. The core forms 9 cells on a 30 square meter plan in zones 1 to 4. All corners of the core are cut back in zones 5 and 6. At the boundary zones or in the corners of the core wall, steel columns with wide flange were designed. There are 8 super columns up to zone 8 and 4 diagonals up to the zone 5. The super columns work together with a layout of eight two-floor high double belt trusses that form an outer mega frame. The outer and inner belt trusses are tied together to form a box-shaped truss to increase torsional stiffness. A tuned mass damper is located in the crown tower at the top of the central core. The inner surface of the building’s crown carries radial outward-sloping cantilevered trusses. The tower is set upon a six-meter deep mat supported by 947 bore piles (1m diameter, 52-56 m long).

Figure 8. The Shanghai Tower - Plan and cross-section
3.6. The Absolute World Towers D and E (Mississauga, Canada)

The Absolute World Towers are a residential condominiums twin tower skyscraper complex in the Absolute City Centre development in Mississauga, Ontario. The buildings are designed by MAD Architects. Absolute Tower Building D (176 m- 56 above ground floors, 6 under-ground floors) has a different height to that of Building E (158 - 50 above ground floors, 6 under-ground floors), Fig. 9. The buildings are designed on an ellipse plan. The design of the Absolute Towers buildings, with their curvilinear form, was inspired by human biological form. This design rejects the conventional idea of a skyscraper as a rigid structure by shifting its attention towards a more delicate form by proposing a human body. The buildings rise from the ground level. The ground floors have a height of 3 storeys supported by columns. This part of buildings have a vertical divisions accentuated by columns and vertical windows. Above, the facade is distinguished by horizontal divisions with strongly extended balconies and glass balustrades and vertical divisions of windows. Balconies cause strong shading in the body. The façade has rectangular windows.

![Figure 9. The Absolute World Tower D – Plan and cross-section](image)

The rotation of the floor slabs, which creates the building’s form, results in a dynamic façade that is different from each viewpoint. Although the initial design involved one tower, the interaction of the two towers has seriously increased the expression of these buildings. The total cumulative rotation of all the floors throughout the building is 205 degrees for Absolute Tower D and 200 degrees for Absolute Tower E. In contrast, the lower building has a higher degree of rotation on individual floors, which gives a subtler visual effect than the taller building which has a significant rotation in the middle. The torsional form of the towers has a simple traditional structural solution. The towers are supported by a grid of load-bearing concrete walls. The bearing walls have different sizes and contrast.
with the sectional fluctuation of the building, which is created by the rotation of the floors and the cantilevered concrete slabs of the balconies. The balconies are an integral part of the curved and twisted construction, giving it the form of a stack of plates. Generally, both towers have the same shape of floor plan while they differ in curvature with respect to the vertical axis. Each floor is rotated by half a degree in the base and on the top floor of the building and by an angle of 1 to 4 degrees in the middle.

3.7. The Agora Garden Tower (Taipei, Taiwan, under construction)

The Agora Tower is a high-rise luxury residential building under construction in the Xinyi District of Taipei, Taiwan, Fig. 10. The building is 93 m height and contains 20 floors above ground and 4 underground. The Agora Tower is designed by Vincent Callebaut. The building is built on the plan of the circle in the central part to which two wings adjoin on the plan of rectangle. The form of Agora Tower resembles the double helix structure of DNA and has two helicoidal towers twisting around a fixed central core. The central part has a diagrid surface (reinforced concrete) with triangular windows. Side wings that radiate around the core have balconies surrounded by greenery and rectangular windows. The ground floor has a height of 2 storeys and is accentuated with columns forming the letter V.

![typical floor plan](image1.png)

![section A-A](image2.png)

**Figure 10.** The Agora Garden Tower – Plan and cross-section

The central core of the building accommodates staircases and elevators. In addition, steel bearing exoskeleton is used to stiffen the structure of the building. All floors are twisted clockwise by an angle of 4.5 degrees and are supported by two spiralling mega-columns. The tower with a double spiral curvature is twisted over the entire height by 90 degrees and has a different shape depending on the direction of view. Its north-south façade has the shape of an inverted pyramid and the east-west façade is shaped like a pyramid with a rhombus base. The levels are structurally supported by a truss system behind the glass facades, which consist of a set of beams for every two floors [11]. The facade is
distinguished by horizontal divisions of balconies, vertical window frames and triangular windows of the central part. The multilayer glass or double layer façades are integrated with blinds to protect the apartments from solar radiation in summers and to reduce thermal loss during winters.

4. Conclusions

Nowadays, twisted high-rise buildings have become a worldwide architectural phenomenon. All buildings over 90 meters, under construction or complete that twist through a gradual rotation of floor slabs is about 30. It is a difficult task for the architects and engineers to design a tall building with a twisting form due to the complex geometrical shapes and interrelationships between non-orthogonal components. Due to the static structure response, twisted forms are not structurally advantageous, because the lateral stiffness of the twisted tower is smaller than that of the straight structure. The lateral stiffness decreases as the rate of twist increases. And this process is accelerated as the building height increases.

This article presents an architectural and structural analysis of seven selected tall buildings with a twisted form, of which three have a residential function (the Cayan Tower, the Absolute World Tower, the Agora Garden Tower), three office function (the Al Bidda Tower, the Evolution Tower, the Shanghai Tower) and one educational (the Mode Gakuen Spiral Towers). Buildings are characterized by different bodies and plans that are not related to the function of the object. They were designed on a convex plane (ellipse, circle, convex triangle), quadrilateral and on complex system. The central core plays a major structural role in all presented buildings. It has the shape of a circle, an ellipse, a square and a cross in the plan. The ground floor was accentuated as a storey with twice height in the Agora Garden, the Mode Gakuen and the Absolute World Tower. In the Al Bidda Tower ground floor is underlined by the vestibule, while the Cayan Tower, the Evolution Tower and the Shanghai Tower in the basement are adjoined by buildings that provide recreation and shopping functions. In five buildings vertical divisions of windows were used in elevations (horizontal balconies are distinguished in the Absolute World Tower and the Agora Garden Tower), while the other two (the Al Bidda Tower and the Mode Gakuen Spiral Towers) have triangular windows associated with the diagrid surface. The Mode Gakuen Spiral Towers and the Shanghai Tower have a double skinned façade. Due to geometric reasons, the most diverse shape is characterized by the Mode Gakuen Spiral Towers and the Agora Garden Tower. However, the most dynamic façade obtained by risalits and window niches has the Cayan Tower.

Mix of complex computing power, new architectural trends and sustainability were the main factors which have been driving this new design. The development of computer technologies and the BIM system had a positive effect on designing of the twisted building. Designers are currently supported by innovative computer software when designing extra-ordinary shapes. In order to simplify the design process, this software must allow rapid shape generations and enable the huge amount of digital data of the components to be handled. In addition, designing the façade system of a twisted tall building, due to its variety, is also a significant issue. However, this complicated form of a high-rise building is not only aesthetic but also plays an important role in the carrying of dynamic loads. The use of aerodynamic twisted forms is an effective method of reducing wind loads on buildings. The effect of the wind on a building is neatly blocked by breaking up the wind flow. Although the cost of erecting such a building is much larger than an orthogonal building, its construction offers the opportunity to test new materials and construction technologies.

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