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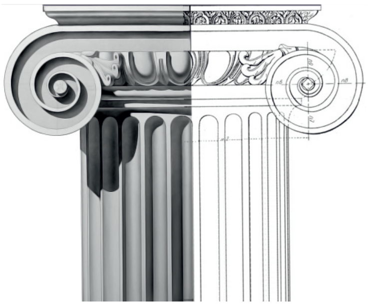

CONTENTS

ASSESSMENT OF THE CORIOLIS FORCE IMPACT ON THE OPERATION OF THE TOWER CRANE SWING MECHANISM

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Abstract

In this paper, issues of the Coriolis force impact on the operation of the tower crane swing mechanism during the starting period under combination of working motions (boom swing and outreach increase) are considered. Quantitative dependencies of the parameters characterizing the mechanism starting mode on the velocity of load trolley travel along the boom and wind load are provided. Diagrams of these dependencies conveniently illustrate a noticeable decrease in the crane output upon adverse combination of factors related to the occurring Coriolis acceleration. More specifically, if the perpendicularly directed heavy wind load influences the boom in case of combination of working motions of the boom swing and outreach change, the starting time constituting the most part of the operating time of the swing mechanism can increase by 20 and more percent. The corresponding methodology of the calculation investigation is also stated in the paper.

Keywords

Swing mechanism calculation, crane mechanism calculation, combination of working motions of the crane, coriolis acceleration, coriolis force

Introduction

Increase in length of the saddle jib and, therefore, increase of outreach are current trends in development of tower crane designs. At the present time, the maximum outreach value is 60–80 meters in large models of the leading global manufacturers. Big length of the horizontal boom enables to simplify the operational cycle of the crane through exclusion of one of four types of working motions, i.e. machine rail travel. Simplification of the crane design, improvement of crane stability and decrease in the labor input of pre-construction activities can be noted as accompanying effects. A large range of changes in outreach also implies the increased travel velocity of the load trolley along the boom (up to 120 meters per minute in modern cranes).

It stands to reason that actual operational cycles are accompanied by combination of motions, in particular, of outreach change (travel of the load trolley along the boom) and boom swing. Upon combination of these motions, the load trolley executes a complex motion along a flat spiral in the fixed coordinate system. It is known from the theoretical mechanics course that even at constant relative velocities of the motions being combined such complex motion is accompanied by a secondary force caused by Coriolis acceleration (Polyakhov, 2015; Teplyakov, 2004). In case of combination of swing with outreach increase, this force creates additional resistance to the swing actuator. The known publications (Aleksandrov, 1986; Vainson, 1989; Gokhberg, 1988) dedicated to the subject of crane mechanism calculation do not mention the force caused by Coriolis acceleration. In this regard, the issue of the necessity to take into account this acceleration in the mechanism design methodology appears to be topical. Investigations in which Coriolis acceleration is taken into consideration when solving a problem of decrease in the load sway on fall ropes of the crane lifting tackle are available. Various solutions are proposed: installation of additional elastic linkages and dampers between the boom and the load (La Duc, 2015), implementation of the complex law of variation of the moving force during mechanism speed-up by means of the control system for the frequency-regulated drive (Naoki Uchiyama, 2013; Tepliakov, 2004), setting of the optimum value of the angular velocity of boom rotation (A. Perig, 2011). The force caused by Coriolis acceleration is proposed to be taken into account upon calculation for not only cranes but also other machines, e.g. excavators — for turnover stability (A. Kholyavko, 2014), log loader working equipment drives (Kolesnikov, 2013).

Materials and methods

Coriolis acceleration is numerically equal to twice the product of the angular velocity of rotation by the linear velocity of the relative motion. The acceleration vector is directed perpendicularly to the radius connecting the rotation axis with the center of gravity of the moving mass (Figure 1).

Thus, Coriolis force moment is numerically equal to the product of Coriolis acceleration by the mass and by the trajectory curvature radius. In relation to the load trolley of the crane, this moment is calculated as the product of Coriolis force by the outreach according to the following formula:

$$M_{Cor} = 2mV\omega R, \tag{1}$$

where: *m* — mass of the load trolley with the load and the hook assembly; *V* — relative velocity of trolley travel; ω — angular velocity of boom rotation; *R* — outreach.

In order to assess the degree of impact of Coriolis acceleration on operation of the swing mechanism, calculation of motion combination impact (swing and outreach increase) for the starting period of this mechanism — by the example of Liebherr 380 EC-B 12 Litronic tower crane — was performed. The crane is equipped with the saddle jib with the maximum outreach of 75 m. The controlled velocity of trolley travel is 0–120 meters per minute. The boom rotation velocity is 0–0.8 rpm. The total power of electric motors of the swing mechanism is 15 kW. Masses and overall dimensions of metal structures and other parts of the crane were taken from the website of the machine manufacturer (see *http://www.liebherr.com/CC/de-DE/region-RU/products_cc.wfw/id-13180-0/measure-nonMetric*).

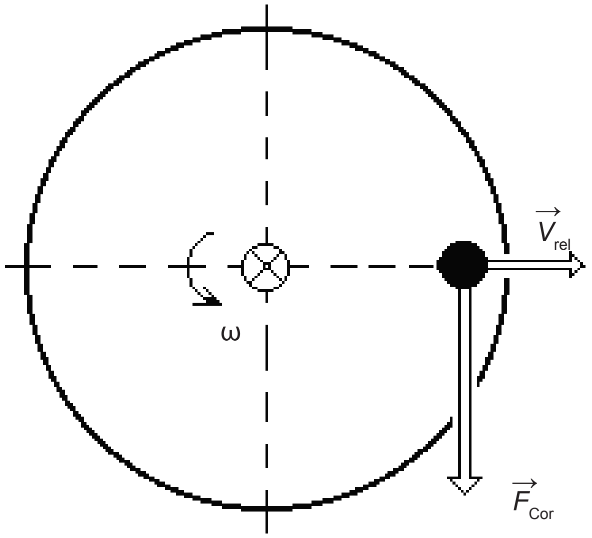

Figure 1. Coriolis force direction upon relative motion of the mass radially

The assumption, according to which the angular acceleration during the starting period changes according to the linear law from initial value ε_1 to final value ε_2, was made. Accordingly, the starting time is calculated as the ratio of the final angular velocity to the average angular acceleration:

$$t = \int_0^{\omega} \frac{1}{\varepsilon}\, d\omega = \frac{2\omega}{\varepsilon_1 + \varepsilon_2}.$$

Angular accelerations are determined on the basis of the equation of traction balance as the abundance of the tractive effort torque (M_{tract} — ΣM_{resist}), divided by total inertia moment J_Σ of rotating parts:

$$\varepsilon = \frac{M_{tract} - \Sigma M_{resist}}{\Sigma J}.$$

The tractive effort torque of the frequency-regulated drive of the crane mechanism is assumed to be approximately constant during the whole starting period (Masandilov, 1998). The starting torque ratio is taken equal to two. The friction losses are taken into account by coefficient of efficiency η = 90%.

$$M_{tract} = \frac{N_{em}\,\eta}{\omega_{nom}}. \tag{2}$$

Generally, the total moment of resistance to the swing consists of moment of friction M_{fr} in the rotation crown, moment of wind loads M_w on the boom and cantilever with counterbalance, and moment M_{Cor} caused by Coriolis force. It is obvious that at the beginning of the starting period M_{Cor} is equal to zero, and further it increases to the maximum value proportionally to the change of the angular velocity and outreach. The moment of wind loads was considered to be constant during the whole starting period of the mechanism.

$$\Sigma M_{resist} = M_{fr} + M_w + M_{Cor}.$$

The well-known methodology (Aleksandrov et al., 1985) was used to determine the moment of friction in the rotation crown in relation to the ball-bearing rotation crown OPU-7 (OP-2500) which is usually used in cranes of domestic production.

Total inertia moment Σ*J* consists of constant inertia moments of the boom with the cantilever and with counterbalance, rotating masses of the drive J_{const}, and of variable mass inertia moments of the load trolley Q_{trol} moving along the boom, hook assembly Q_h and load Q_l (J_{var} depends on the outreach):

$$J_{var} = \frac{Q_{trol} + Q_h + Q_l}{R^2}; \tag{3}$$

$$\Sigma J = J_{const} + J_{var}.$$

In view of the aforesaid, the starting process can be described by four dependencies:

$$\varepsilon_1 = \frac{M_{\text{tract}} - \mathrm{M}_{\text{fr}} - M_{\text{w}}}{J_{\text{const}} + J_{\text{var}}}; \tag{4}$$

$$\varepsilon_2 = \frac{M_{\text{tract}} - \mathrm{M}_{\text{fr}} - M_{\text{w}} - M_{\text{Cor}}}{J_{\text{const}} + J_{\text{var}}}; \tag{5}$$

$$\mathrm{t} = \frac{2\,\omega}{\varepsilon_1 + \varepsilon_2}; \tag{6}$$

$$R = R_0 + V\mathrm{t}, \tag{7}$$

where R_0 is the outreach at the initial moment of the mechanism starting period.

Formula 7 is used upon calculation of J_{var} and $M_{\text{Cor.}}$ After substitution of (7) in (1), and (3), (2) — in (4), (3) — in (4) and (5), (4) and (5) — in (6) and subsequent algebraic transformations, the above-mentioned dependencies are reduced to the cubic polynomial with constant coefficients A_1, A_2, A_3, and A_4:

$$A_1 t^3 + A_2 t^2 + A_3 t + A_4 = 0.$$

Hence, the required starting time is calculated as the root of the cubic equation.

Two options of crane operation according to the load were subject to calculation:

1) load mass Q = 12,000 kg, equal to the maximum safe working load, velocity of the load trolley V = 60 meters per minute, equal to the half of the maximum value;

2) load mass Q = 6,000 kg, equal to the half of the maximum safe working load, velocity of the load trolley V = 120 meters per minute, maximum.

In both options, outreach at the initial moment of the starting period R_0 = 7 m, boom rotation velocity after starting is 0.8 rpm.

Results

The calculation results (Figure 2, Figure 3, Figure 4) indicate the impact of such factors as the velocity of trolley travel along the boom and wind load on starting parameters. The zero velocity means that the combination of motions does not happen and, therefore, Coriolis acceleration is absent. In the calculations, the direction of the wind load vector is accepted perpendicularly to the boom, which is the worst option creating the highest resistance to its swing.

Conclusions

The analysis of the presented results enables to draw the following conclusions:

1. The consideration of Coriolis acceleration at the starting of the crane swing mechanism upon combination of motions can change noticeably the calculation results of such parameters as starting period duration and angular acceleration at the final stage of the starting period. The increase of the starting time constituting the most part of the operating time of the swing mechanism can exceed 20%.

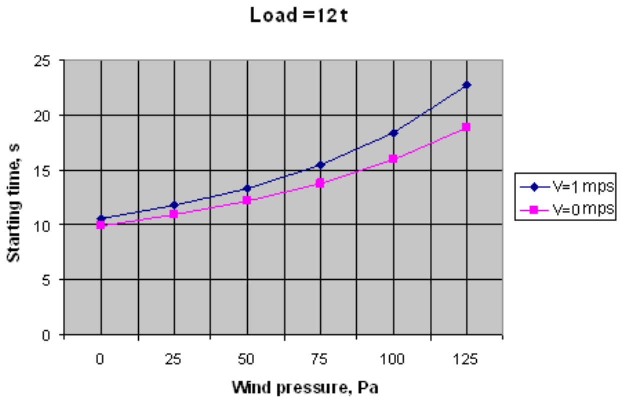

Figure 2. Swing mechanism starting time with a load of 12t under the conditions of various wind pressure intensities (upon combination of operations (V = 1 mps) and without such combination (V = 0 mps))

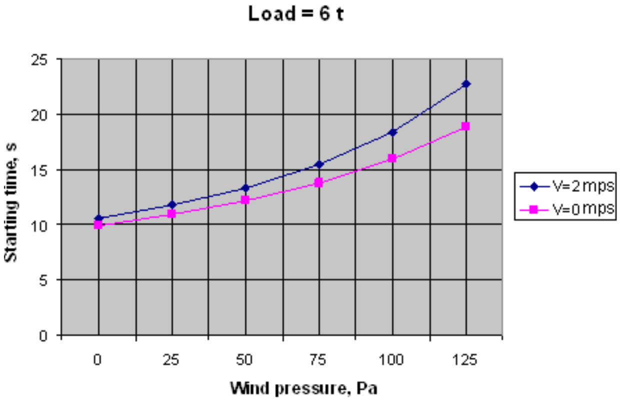

Figure 3. Swing mechanism starting time with a load of 6t under the conditions of various wind pressure intensities (upon combination of operations (V = 2 mps) and without such combination (V = 0 mps))

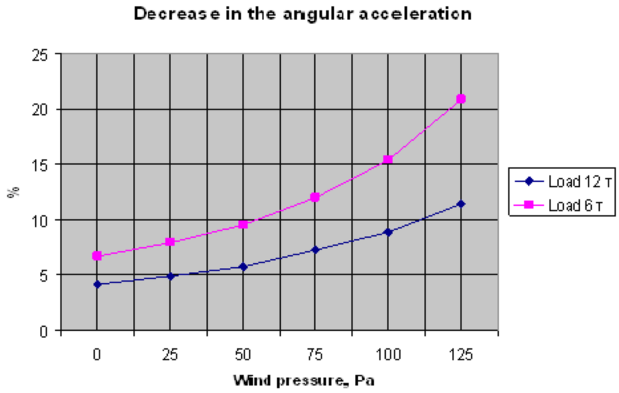

Figure 4. Relative decrease in the angular acceleration of the boom by the end of the starting period, caused by combination of operations under the conditions of various wind pressure intensities

2. The impact of Coriolis acceleration becomes significant upon adverse combination of two factors: high velocity of load trolley travel along the boom and high resistance to the swing caused by the wind

load which is transversal to the metal structures of the boom.

3. It is necessary to take into account the Coriolis acceleration factor for tower cranes with high velocity of the trolley upon calculation of the swing mechanism capacity, and the corresponding issue is quite topical.

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FROM THE BASICS OF SPATIAL CONSTRUCTIONS TO CONSTRUCTION OF AN IMAGE (a case study of engravings by Giovanni Battista Piranesi)

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Abstract

The article deals with the exhibition “Piranesi. Before and After. Italy–Russia. XVIII–XXI Centuries” held at the Pushkin State Museum of Fine Arts in Moscow in autumn, 2016. The exhibition revealed a new scientific interest to the creative heritage of the architect.

The author of the article visited the exhibition. During the analysis of the exposition, she discovered a justification of the hypothesis on existence of a common visual language in architectural graphics of G. B. Piranesi. Through the case study of the series “Antique Vases, Candelabra, Tombstones, Tomb-Chests, Trivets, Braziers, and Ancient Carvings…” the author examines the hornbook of “spatial constructions” of the artist.

Piranesi creatively interpreted techniques of Andrea Palladio’s architectural graphics and introduced in them a “plasticity approach” peculiar for the art of theatrical scenery of his teacher Giuseppe Valeriani. He created a system of contrasting structural arrangements where angular and front perspectives appeared to be alignment elements, visually connecting different sketch sheets of the series. Following this approach, a geometric arrangement of his engravings acquired new features different from those used in the Andrea Palladio’s “orthogonal approach” and form arrangement with the help of drawings and perspective geometry used by his contemporaries.

Multi-dimensional and multi-layered graphics is a composition technique typical of his engravings of other series, such as “Raccolta di varie vedute di Roma si antic ache moderna, intagliate la maggior parte dal celebre Giambattista Piranesi e da altri incisori” (“Collection of various views of Rome ancient and modern…”) (1752). The synthesis of “linear” and “plastic” approaches in arrangement of a composition, when different principles prevail at certain stages is one of the factors affecting formation of individual visualization in his work. To illustrate this fact, we looked at compositional sketches of his predecessors, like G. Valeriani and M. Ricci. Using the example of one of the engravings by Piranesi (series “Carceri” (“Prisons”)) we will show the process of forming the plastic composition.

In the process of compositional analysis of sketch sheets of the series “Antique Vases, Candelabra, Tombstones, Tomb-Chests, Trivets, Braziers, and Ancient Carvings…”, we for the first time proposed mechanisms for determining the compositional center in the “three-dimensional” system of G. B. Piranesi’s architectural graphics.

Keywords

Language of architectural graphics, composition, angular perspective, spatial constructions, drawing, orthogonal projections, geometric structure, image

Introduction

During 20 September and 13 November 2016, the exhibition “Piranesi. Before and After. Italy–Russia. XVIII–XXI Centuries” was held at the Pushkin State Museum of Fine Arts in Moscow. This exhibition project hada great international resonance; supervisors of the exhibition were:

- Art and architecture historian Federica Rossi known as the author of numerous works devoted to architecture and artistic culture of Russia and

Italy; a representative of the German Institute of Art History in Florence. Since 2012, she has been a visiting professor at the department of art and architecture history at the Moscow Architectural Institute (MArchI).

- Semen Mikhailovsky, the rector of the I. Repin St. Petersburg State Academy Institute of Painting, Sculpture and Architecture at the present time. Professor Emeritus of the Moscow Architectural Institute.
- Marina Mayskaya, a leading researcher and a supervisor of the Graphics department at the Pushkin State Museum of Fine Arts, a specialist on Italian drawing of XV–XX centuries, an author of a three-volume catalogue-raisonne on Italian drawings from the collection of the Pushkin State Museum, as well as an author of numerous books and articles on the art of drawing.

The exhibition was located in five halls and on the walls of the Main Staircase. Three permanent exhibition halls No. 30, 19 and 20 and two temporary halls No. 18 (previously used for Spanish and Italian art of the XVIII century) and No. 21 (French art of the XVII century) were allocated for the exposition (Figure 1).

Supervisors of the exhibition Federica Rossi, Semen Mikhailovsky, Marina Mayskaya, and Yuliya Merenkova included objects from the collection of casts made from antiques exhibited in the Pushkin State Museum of Fine Arts in Moscow into the exposition: plaster and bronze coated casts, electrotype copies of household items found during archeological excavations at Pompeii and Herculaneum. Cork models from the collection of the Russian Academy of Fine Arts Museum (Pantheon, Piramide Cestia, etc.) decorate the exposition (Figure 2).

As a part of the exhibition project, various meetings for adults and children are held in the museum halls and the lecture class (Prince Golitsyn Family Estate

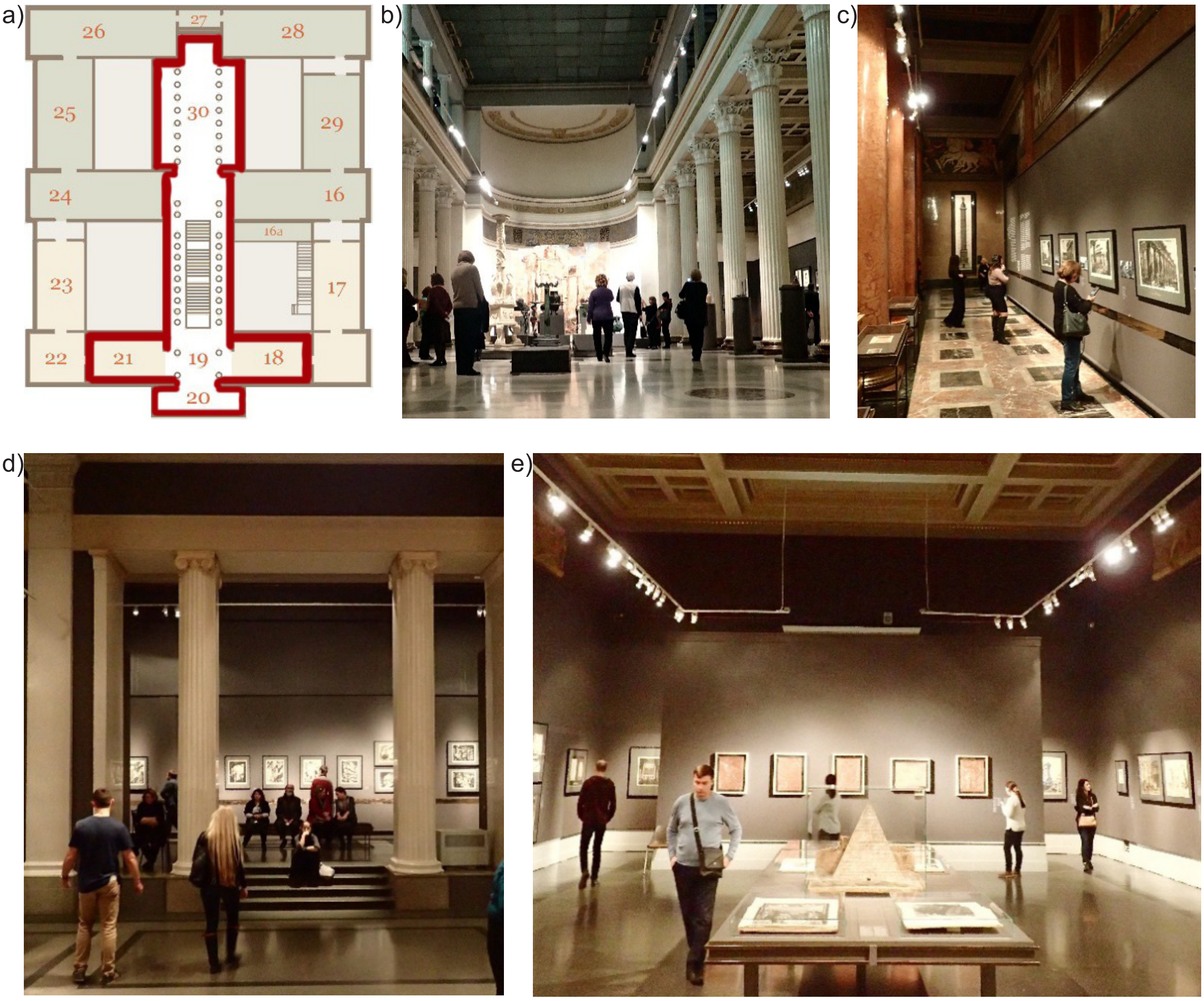


Figure 1. “Piranesi. Before and After. Italy–Russia. XVIII–XXI Centuries”. Photos by E.A. Chernaya. Interiors of the Pushkin State Museum of Fine Arts where the exhibition took place: a) second floor plan of the Pushkin State Museum of Fine Arts (highlighted in red); b) exhibition hall No. 30; c) Main Staircase; d) exhibition hall No. 20; e) hall No. 18

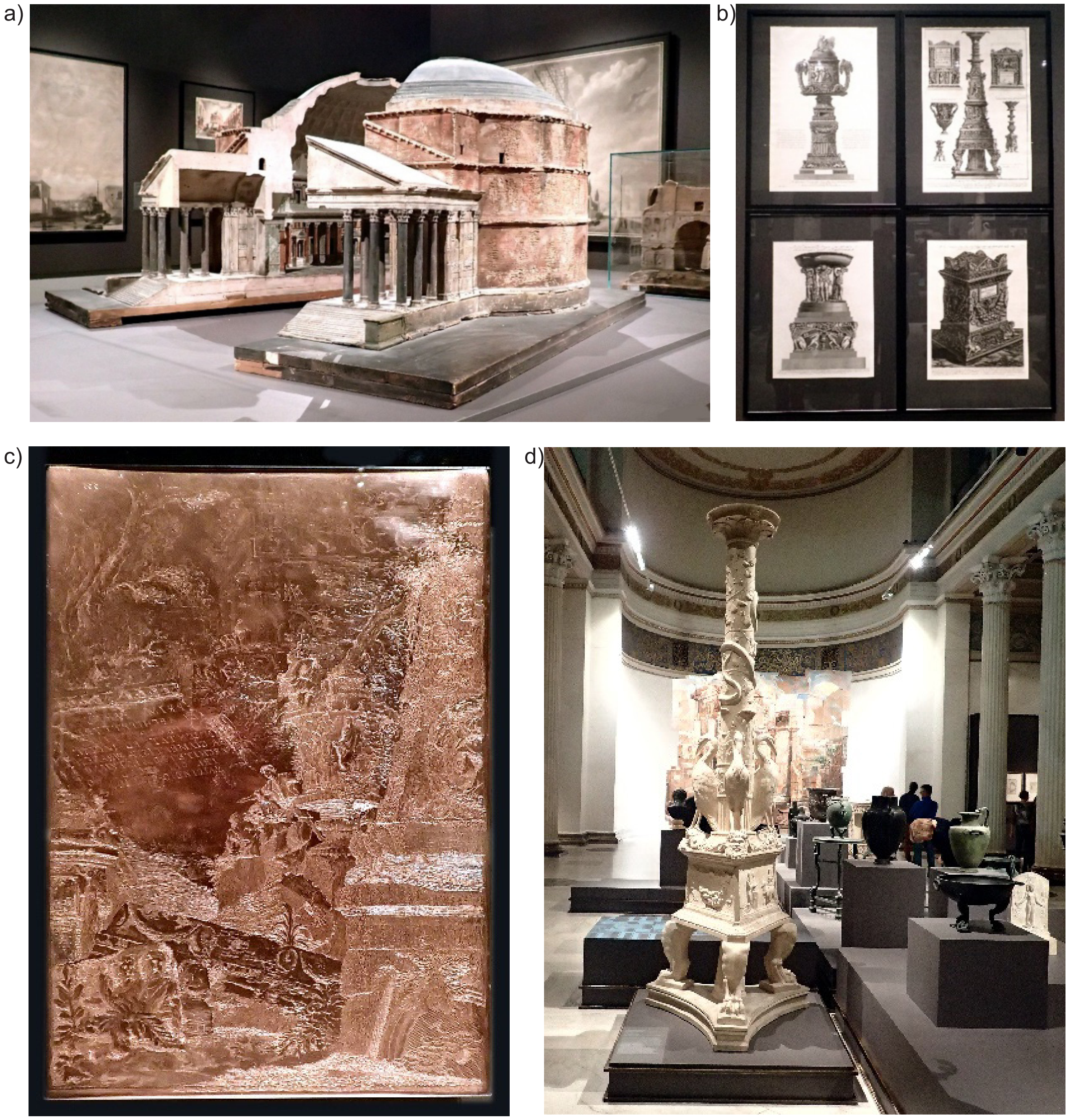


Figure 2. “Piranesi. Before and After. Italy–Russia. XVIII–XXI Centuries”. Photos by E.A. Chernaya. Exposition of the exhibition: a) architectural model of the Pantheon; b) engravings of G. B. Piranesi and his assistants F. Piranesi, Brenna, and graphics of European, Russian, Soviet architects; c) a copper plate engraved by G. B. Piranesi; d) candelabrum with storks (tinted plaster, casting from a model. Original work: XVIII century marble)

located near the main building of the museum); at the meetings they reveal the phenomenon of architectural graphics of G. B. Piranesi and the role of his graphic heritage in the artistic culture of the following centuries until the second half of the XX century.

A fundamental catalogue was issued in the Pushkin State Museum of Fine Arts; it included articles by leading Russian (Marina Mayskaya, Dmitry Shvidkovsky, Semen Mikhailovsky, Nikolay Molok) and West-European researchers (Federica Rossi, Maurizio Calvesi, Letizia Tedeschi, Ginevra Mariani et al.). The articles disclosed the following topics of the exhibition:

1. From theatrical scenery to the series “Carceri”.
2. From “Collection of monuments of the Eternal City” to the series “Paestum”.
3. Piranesi and study of the ancient heritage.
4. Piranesi. Ancientry as a source of inspiration.
5. Piranesi and Russian architecture of the XVIII century.
6. Piranesi and Soviet architecture.

Such a variety of topics for scientific research of the artistic heritage of G. B. Piranesi evidences both of tradition and novelty of graphical language, which we try to reveal in this article.

Methods and Materials

Piranesi's graphical artistic culture formed during studying and working with famous masters of various directions of plastic arts, who influenced his compositional thinking, which manifested in geometric arrangement of his works. In this article we analyzed some sheets of the series "Antique Vases, Candelabra, Tombstones, Tomb-Chests, Trivets, Braziers, and Ancient Carvings…" where the architect sought to convey spatial representation of the shape in the plane to the viewer. He recreated whole ancient antiquities on his engravings taking only their fragments as the basis.

Our study focuses on the analysis of arrangement of geometrical and plastic structures in Piranesi's works.

The sketches clearly reveal professional nature of the artist's drawings. Piranesi's sketches constitute a rather small group of the exposition. They are valuable because they assert a main "driving idea" (the term by Yu. I. Kurbatov) of the author that clears up everything unnecessary, facilitating alignment of the image in the mind of the artist followed by arrangement of a hierarchical structure and the elements of the composition in the plane in the course of his artistic work. Then, the idea solidifies and gets its material embodiment in the process of a continuous work on a compositional sketch in the plane or on an architectural project.

Since the exhibition presented some sketches of scene painters (Giuseppe Galli Bibiena, Giuseppe Valeriani, Angelo Toselli, Pietro di Gottardo Gonzago) and classicist architects (Francesco Galli Bibiena, G. B. Piranesi, Jean François Thomas de Thomon), as well as sketches of Soviet architects, performed in the framework of competitive projects (Ivan Aleksandrovich Fomin, Boris Mikhailovich Iofan, Arkady Grigoryevich Mordvinov, Lev Vladimirovich Rudnev and others) (Figure 3), we had a chance to carry out a comparative analysis of exhibited sketches and compare them with other published works in other editions.

We were looking for an answer to the question whether there were common visually apparent signs of a single compositional language in Piranesi's prints (of high artistic value and those considered to be less expressive, i.e. orthographic and axonometric projections)? We suppose that his system of architectural graphics may have been found and caught up by his followers, classicist artists and artists of the Soviet period. Did they use the same hornbook of "spatial constructions"? We borrowed this concept from the work of B. V. Rauschenbach (1975) to emphasize the meaning of the perspective as a means of the composition.

In order to reveal hidden compositional patterns in graphics, we took a sketch by G. Valeriani (Figure 4) presented at the exhibition and compared it with a reproduction of a sketch of a design scenery for the opera "Scipione" represented in the work of M. S. Konopleva "Scene painter Giuseppe Valeriani" (1948).

It should be noted that G. B. Piranesi "worked with stage designers from Rome, brothers Domenico and Giuseppe Valeriani" (Sorokina, 2007), the apprentices of Venetian Marco Ricci (the master of Capriccio, who also painted fictional landscapes with ancient Roman ruins and stage scenery). According to researcher N. I. Sorokina, Piranesi "conceived the style" of Ricci through this acquaintance (Sorokina, 2007).

When comparing two sketches of Marco Ricci and G. Valeriani, it can be seen that both are performed in the system of angular perspective, which then was so skillfully mastered by G. B. Piranesi. Drawings of the mentioned artists have the same compositional pattern. Since there is no data on the further development of Marco Ricci's sketches, we undertook a compositional analysis of G. Valeriani's works (Figure 4).

The first sketch of G. Valeriani is different from the project scenery in relation to its geometry: it has a square shape, while the other is rectangular. The stage painter captured all the elements of his future composition on the sketch and then aligned visually, plastically and constructively all these parts on the draft, forming a coherent structure (Fig. 4). Later, G. B. Piranesi learned these lessons of composition and interpreted those compositional techniques artistically in the series "Carceri".

Let us return to the analysis of the exposition. The following stand excited our interest in the central zone of hall No. 30. The fact is that Piranesi headed a restoration workshop and sales of antiques. Piranesi recreated objects of Roman utensils in his engravings on the basis of small original fragments.

The first Piranesi's workshop was situated "on Via del Corso close to the French Academy" (Sorokina, 2007), and the second workshop was "on Via Sistina" (Sorokina, 2007). As we know, the French Academy was housed in the Mancini palace (Italian: Palazzo Mancini) in Rome in the period from 1737 to 1793.

"Students of the French Academy often worked with Piranesi" (Sorokina, 2007) and adopted his technique of "split-second method of drawing", i.e. "grasping of the main idea, colored by emotions and life clear of stiffness and vanity" (Sorokina, 2007). A very small number of Piranesi's sketches preserved, as he had the following opinion (according to J.-G. Legrand): "if my drawing is complete, then my engraving would be nothing more than a copy, while on the contrary, I draw my immediate impressions on

Figure 3. Sketches of scene artists and architects presented at the exhibition “Piranesi. Before and After. Italy–Russia. XVIII–XXI Centuries” and in the catalogue: a) G. Valeriani. The courtyard of the prison. 1740s. Pen, brush, bister, ink, 147x241. Pushkin State Museum of Fine Arts, Moscow; b) Pietro di Gottardo Gonzago. View of the city square and streets. Blue paper, pen, brush, bister, ink, watercolors, pencil. 181x271. Pushkin State Museum of Fine Arts, Moscow; c) G. B. Piranesi. The Arch of Gallienus in Rome. 1740s. Watercolors, pen, ink, pencil. Estense University Library, Modena; d) I. A. Fomin, The building of the Kursk railway station. The perspective through a colonnade of roundabout galleries. Competitive project. 1933. Tracing paper, pencil, charcoal, pastel. 43.5x53.5. Shchusev State Museum of Architecture, Moscow; e) B. M. Iofan. Sketch adopted as the basis for the project of the Palace of the Soviets in Moscow. Perspective. 1933. Version. Tracing paper, charcoal, lacquer, 39.4x70.3. Shchusev State Museum of Architecture, Moscow

a copper sheet, creating an original work” (Sorokina, 2007).

What did Piranesi mean with “immediate impression”? As we know, the technology of etching transfer on the plate is carried out with a tracing paper. The main line and outlines are transferred on the plate. Then, linear outlines and the shape are specified.

Before we start to examine the compositions of Piranesi’s engravings in the series “Antique Vases, Candelabra, Tombstones, Tomb-Chests, Trivets, Braziers, and Ancient Carvings…” published in 1778, we would like to give a short review of the articles on the subject. Some researches focus on the issue of the historical background of the origin of the engravings and their spatial composition (N.I. Sorokina (2005), Yu. Maiskaya (Rossi, 2016), P. Panza (2013), W. Rieder (1975)). The other group of researches prefers to describe the copies of the original works or the series sheets (e.g. T. Il’ina) (Rossi, 2016), or consider the series of engravings as the basis for material art or jewellery (Lowe, 2011; Wees, 2007; D. Udy, 1978).

Fig. 5 gives a comparative analysis of the composition of the engraving “The staircase with trophies”, Sheet VIII, State V, the series “Carceri” (1749) (Sorokina, 2005), and its comparison with the sketch “Interior of an imaginary prison with trophies”

Figure 4. Angular perspective in graphics of Marco Ricci and G. Valeriani. From a sketch to a draft version of the scenery:
a) Marco Ricci. The courtyard of an imaginary palace. Drawing, the first half of the XVIII century, Royal Collection, Windsor Castle, Windsor, England; b) G. Valeriani. The interior of the palace hall. Pen, brush, bister, traces of pencil. 170x208, around 1745. Pushkin State Museum of Fine Arts, Moscow; c) G. Valeriani. Draft decoration of the opera “Scipione”, State Hermitage, St. Petersburg (Konopleva, 1948)

(1740) (Ippolitov et al., 2011). We revealed a contrast change of plastic composition of the engraving according to its different states. G. Piranesi changed the initial plastic hierarchy of the spots on the plane, thus looking for the ways to capture his “immediate impression”, which we understand as spatial view of the represented object. The engraving shows a compositional consistency of the depicted objects on the spots, which can be observed on the first sketch and the first state of the engraving. Further the configuration of elements and their “spatial alignment on the drawing” (the term by B. V. Rauschenbach) are adjusted. Their compositional hierarchy changes (Figure 5). An in-depth space movement starting from the image plane boundaries (layout) prevails on the sketch and the first engraving of State I, while opposite movement out of depth can be observed on the engraving of State V. The latter engraving comprises a dynamic equilibrium of both forces, which helps the viewer to form a complete image of a closed architectural space and visual movement during viewing of the engraving. The artist leads the viewer’s glance by means of the composition arranged according to the “labyrinth” principle, when one gets at one and the same point of the compositional center of the engraving, no matter where one’s glance is wandering.

As we know, in architecture, “the compositional center is correlated with the main parts, based on rhythmic order and contrasting oppositions. Identification of the compositional center is provided with intergrowth of intensity of one or a group of properties and their maximum intensity in the predominant part of the architecture” (Ikonnikov,

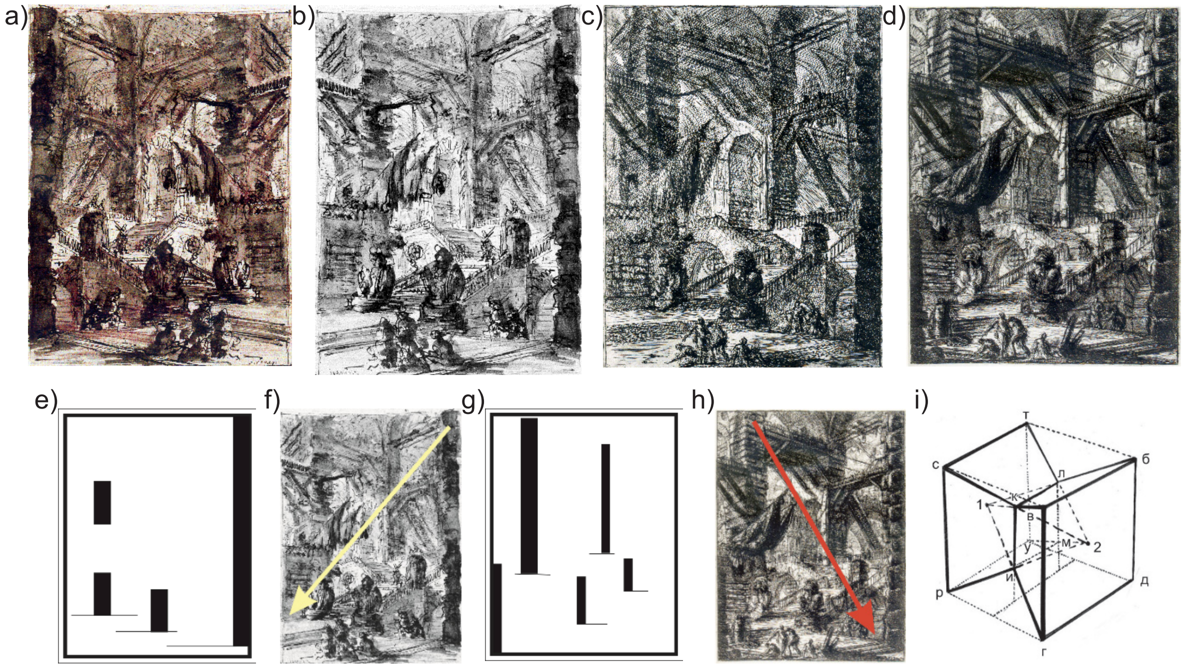


Figure 5. Series “Carceri” (1749): a) G. B. Piranesi. Interior of an imaginary prison with trophies. Pen and brush of brown tones, red chalk. 1740s. Kunsthalle, Hamburg; b) mirrored G. B. Piranesi’s sketch performed in Corel Photo-Paint; c) The staircase with trophies. Sheet VIII. Etching with chisel, 561x415. State I. State Hermitage, St. Petersburg; d) The staircase with trophies. Sheet VIII. Etching, chisel, 550x405. State V. Pushkin State Museum of Fine Arts, Moscow; e) a pattern of distribution of black spots on a sketch and engraving of State I; f) direction of the engraving space in-depth created by spots; g) a pattern of distribution of black spots on an engraving of State V; h) direction out of depth of the engraving space created by spots; i) a cubic model reflecting the principle of spatial constructions of the plastic arrangement of spots in the plane, revealing a compositional and spatial thinking of G. B. Piranesi

2001). For the purposes of the analysis of the composition of the engravings included in the series “Antique Vases, Candelabra, Tombstones, Tomb-Chests, Trivets, Braziers, and Ancient Carvings…”, let us determine the compositional center as a part of the image (element, area, object, or space) which geometric, rhythmic, sculptural, and qualitative features contrast with its environment. It prevails over other parts in structural hierarchy of compositional elements. An image may show several centers, according to focus of our analysis, i.e. form, space, or plane, which may result in revealing the objective, spatial, and planar centers. Their correlation indicates the final position of the compositional center. The following types of spot contrasting are used for visual detection of the Piranesi’s engraving center: lightness, orientation, size, etc. The text on the image also accentuates the plane and focuses the viewer’s attention on the main center.

It should be noted, that not all reproductions contain the explanative text on Piranesi’s engravings, though such text is essential for compositional integrity of the image. For example, reproduction published in 1905 (Vincent, 1905) contains either a part of the text or no text at all. The album published in 2000 shows the full text (see Figure 6).

Hall No. 30 held Piranesi’s architectural graphics, the series “Antique Vases, Candelabra…” We revealed certain logic of compositional arrangement of the works due to the order of their hanging.

On the one hand, while the drawing method (parallel projection onto the plane) remains within the conventional system of shape arrangement, the graphics is not divided into two parts, “technical” (drawing, sketch, demonstration drawing with pattern entities) and “artistic” (image) (Ikonnikov, 2001), remaining a single unit, where one part amplifies “ideological and artistic side” of the work, and the idea of the artist (Rauschenbach, 1975).

We changed the sequence of sheets of the G. B. Piranesi’s series “Antique Vases and Candelabra” to reveal hidden internal compositional logic of their arrangement.

For graphic recreation of antique objects, he used angular and front perspectives. Previously, angular perspective was widely used by stage painters and accomplished with the help of orthogonal projections of the plane and the face of the perspective view of the interior. Stage painter Ferdinando Galli Bibiena described the method of its construction in his treatise (1711) (Figure 6).

Architectural graphics, “technical drawings” by Piranesi are not two-dimensional, but three-dimensional (x, y, z). The compositional center is located on the axis, the base of which is fixed on the

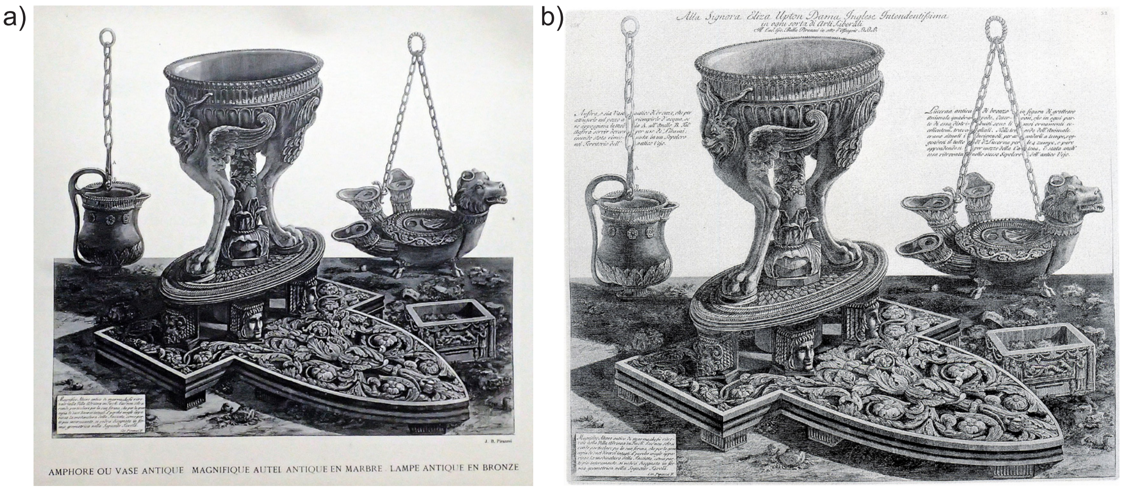
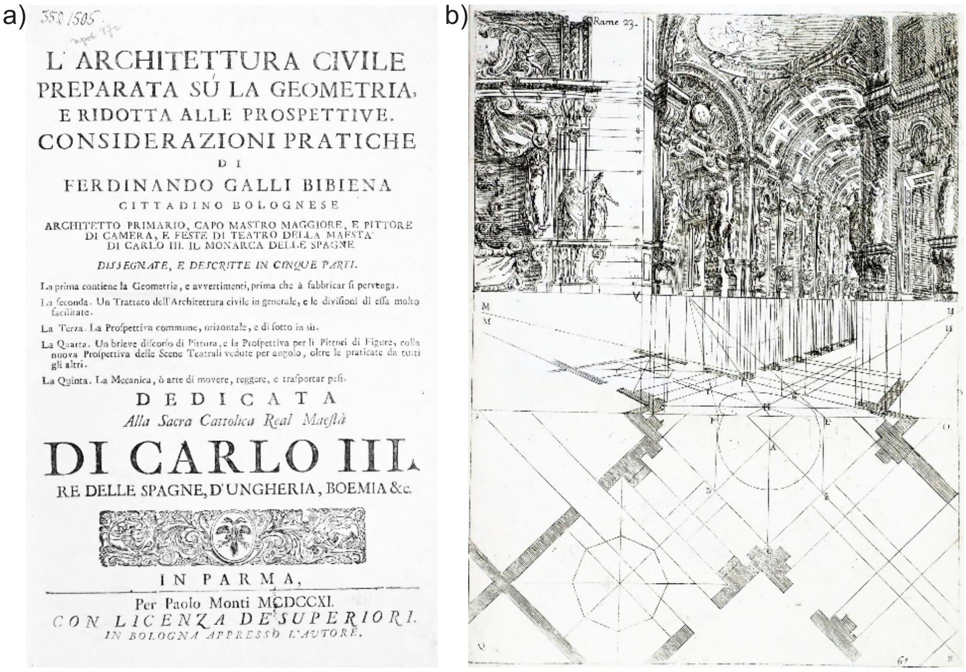


Figure 6. On compositional integrity of the engravings: a) reproduction of Piranesi's vase ("Amphore ou vase antique en bronze") published in 1905 (Piranesi J.-B. Vases, candelabres sarcophacges, trepieds lampes et ornements divers: reproduction de l'edition originale. – Paris: Auguste Vincent, editeur, 1905). SPSUACE Main Library; b) reproduction of "Amphore ou vase antique en bronze" published in 2000 (text preserved) (Ficacci L., Giovanni Battista Piranesi: The compl. etchings / Luigi Ficacci. – Köln etc : Taschen, cop. 2000. – 799 c.)

intersection of diagonal directions in the cubic space of the engraving (Figure 8 e, f, h, i).

Figure 8 shows different compositions on the sheets of the series "Vases…" The compositional center is moved above the geometric center on one works and below the geometric center on other works. The artist uses compositions with two or three centers, when single compositional center splits to sub-centers. As we know, two intersecting diagonal lines starting from the boundaries of the engraving reveal its geometric center; two intersecting directions in space may also indicate the spatial center. The author indicates the start point of "in-depth diagonal movement" (term of art), which starts from the boundaries, by means of the plane marked by the explanatory inscriptions.

Piranesi applies a range of techniques to induce spatial perception of the depicted objects. The first compositional technique is based on the contrast between the shape of the object and plane background, which is intensified by the explanatory inscriptions. The compositional center coincides with the geometric center (see Figure 8 a, b).



L' ARCHITETTURA CIVILE
PREPARATA SU LA GEOMETRIA,
E RIDOTTA ALLE PROSPETTIVE.
CONSIDERAZIONI PRATICHE
DI
FERDINANDO GALLI BIBIENA
CITTADINO BOLOGNESE
ARCHITETTO PRIMARIO, CAPO MASTRO MAGGIORE, E PITTORE
DI CAMERA, E FESTE DI TEATRO DELLA MAESTA'
DI CARLO III. IL MONARCA DELLE SPAGNE
DISSEGNATE, E DESCRITTE IN CINQUE PARTI.

La prima contiene la Geometria, e avvertimenti, prima che à fabbricar ſi pervenga.

La ſeconda. Un Trattato dell'Architettura civile in generale, e le diviſioni di eſſa molto facilitate.

La Terza. La Proſpettiva commune, orizontale, e di ſotto in sù.

La Quarta. Un brieve diſcorſo di Pittura, e la Proſpettiva per li Pittori di Figure, colla nuova Proſpettiva delle Scene Teatrali vedute per angolo, oltre le praticate da tutti gli altri.

La Quinta. La Mecanica, ò arte di movere, reggere, e traſportar peſi.

DEDICATA
Alla Sacra Cattolica Real Maeſtà
DI CARLO III.
RE DELLE SPAGNE, D'UNGHERIA, BOEMIA &c.

IN PARMA,
Per Paolo Monti MDCCXI.
CON LICENZA DE' SUPERIORI.
IN BOLOGNA APPRESSO L'AUTORE.

Figure 7. Ferdinando Galli Bibiena's treatise (1711) stored in the SPSUACE Main Library, Saint Petersburg: a) the title page; b) angular perspective through the example of the interior

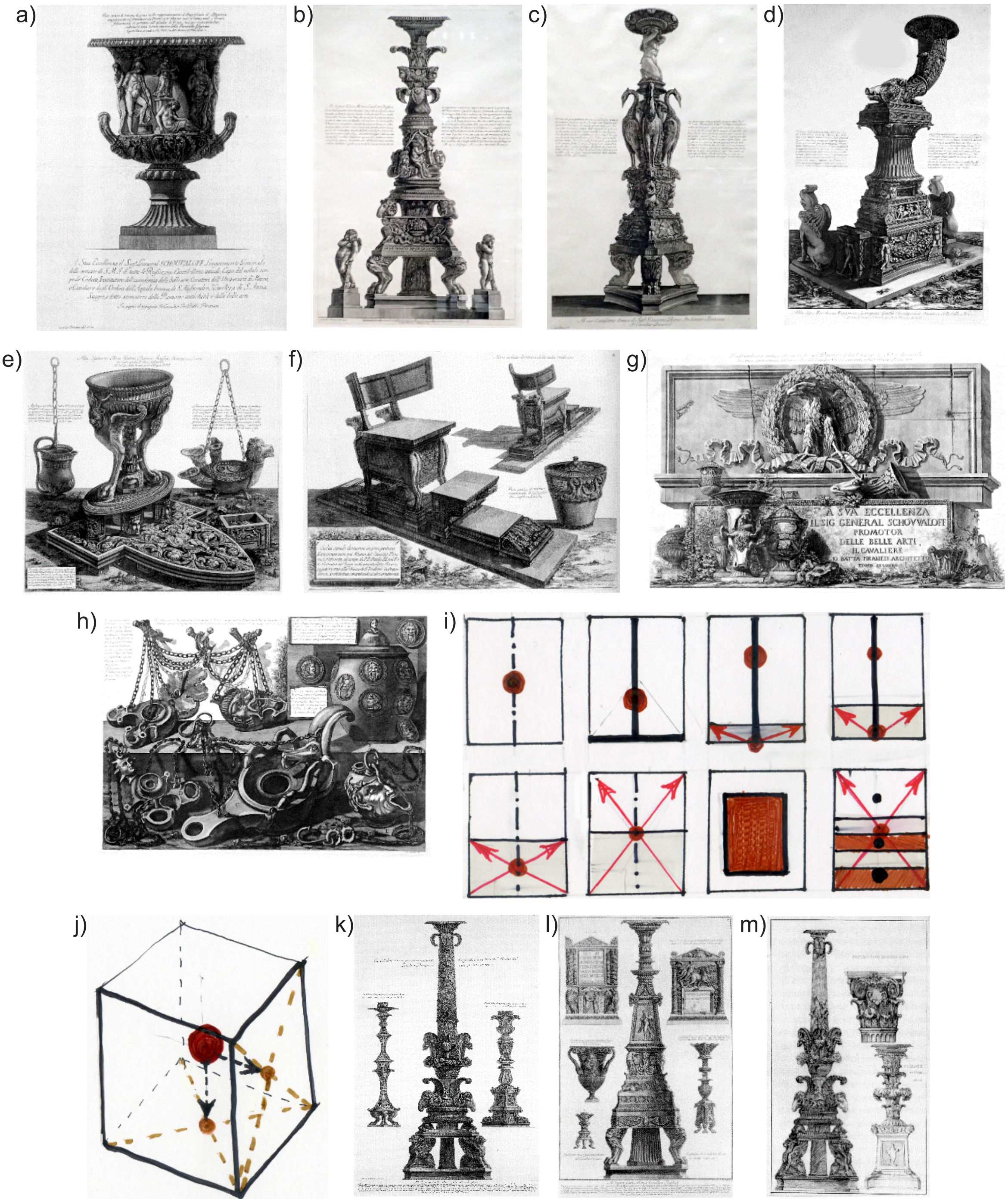


Figure 8. The hornbook of spatial constructions of composition in the plane through the example of the series of engravings “Antique Vases, Candelabra…” by G. B. Piranesi (Pushkin State Museum of Fine Arts, Moscow) (Sorokina, 2005).
The basic principles of the first stage of composition (work with the compositional center):
a) marble vase with a scene of Iphigenia sacrifice. Etching, chisel, 530x390. Engraved by Piranesi;
b) candelabrum from the Palazzo Salviati (Piranesi’s candelabrum), 655x410. Engraved by Piranesi;
c) perspective view of a large marble candelabrum found at Hadrian’s Villa in Tivoli. Etching, chisel, 663x415. Engraved by Piranesi;
d) funerary monument completed with a rhyton with a boar head. Etching, chisel, 670x420. Engraved by Piranesi;
e) ancient marble altar, bronze lamp and vase. 448x495. Engraved by Piranesi;
f) curule seat and marble vase. Etching, chisel, 385x530. Engraved by Piranesi;
g) various lamps and a vase encrusted with cameos. 388x535. Engraved by Piranesi;
h) the title page of the second volume of the series with ancient relief of the portico of the Santi Apostoli church in Rome. Etching, chisel, 480x715. Engraved by Piranesi;
i) three candelabra. Etching, chisel, 685x435. Engraved by Piranesi;
j) projection of a form in the geometric center on orthogonal planes;
k) three candelabra, a vase and two funeral urns. Etching, chisel, 675x432. Engraved by Piranesi;
l) three candelabra, a vase and two funeral urns. Etching, chisel, 675x432;
m) in future, this combination of imaging would be continued in the academic work of student architect N. D. Kolli “Academic work “Ancient Rome”. Paper, pencil, ink.

The second technique comprises formation of image depth by means of angular perspective. In this case, G. Piranesi uses alternation of angular and frontal planes for finding their equilibrium. The compositional equilibrium axis is fixed by intersecting diagonal directions formed by the planes of the objects depicted. The compositional center is displaced rightwards from the geometric center (see Figure 8 c, d, e, f).

The third technique is formation of space depth by means alternation of orthogonal projections. The projections in this case vary in their spots dimensional characteristics and include the elements similar in certain parameters. Such compositional technique ("scale leap") implies scaling of a spot on a second ground and helps to create an illusion of depth on a plane (see Fig. 8 k, l, m).

The fourth technique is to emphasize a frontal perspective. The compositional center is scattered between several sub-centers which form the area of the main compositional center of the picture see Figure 8 i).

As we know, G. B. Piranesi's series of engravings "Antique Vases, Candelabra…" had been published since 1768 ("since 1768, the beginning of publishing of individual engravings of ancient monuments of applied art") (Sorokina, 2005). This information, as well as the comparative analysis of the part of the series sheets, allows us to declare that the architect affirmed a hornbook of compositional techniques of his spatial constructions, which he had previously tried in the series "Raccolta di varie vedute di Romma…" (Collection of Various Views of Rome…) (1752). Here the composition is formed by means of blending and synthesis of several structures, different levels, while in "Antique Vases, Candelabra…" it is more visual.

Engravings of the series "Views of Paestum" are exhibited as a part of the exposition located on the Main Staircase. Supervisors of the exhibition accompanied them with photographs made by Gianluca Baronchelli in 2016; these photos illustrate the same point of the landscape viewing in photographs and Piranesi's engravings, which facilitates the disclosure of Piranesi's compositional thinking during their comparison (see Figure 9).

The visual comparative analysis of these engravings and photographs results in detection of multiple viewpoints (arranged along one horizontal axis). J. B. Rapp (2008) also described this phenomenon, though she examined another series of Piranesi's engravings. Applying multiple viewpoints on the engraving, the architect evaded the angle view that we can observe on photographs, where objects out of a "clear vision" change their geometric dimensions (elongate) due to the peculiarities of human visual perception (Rieder, 1975).

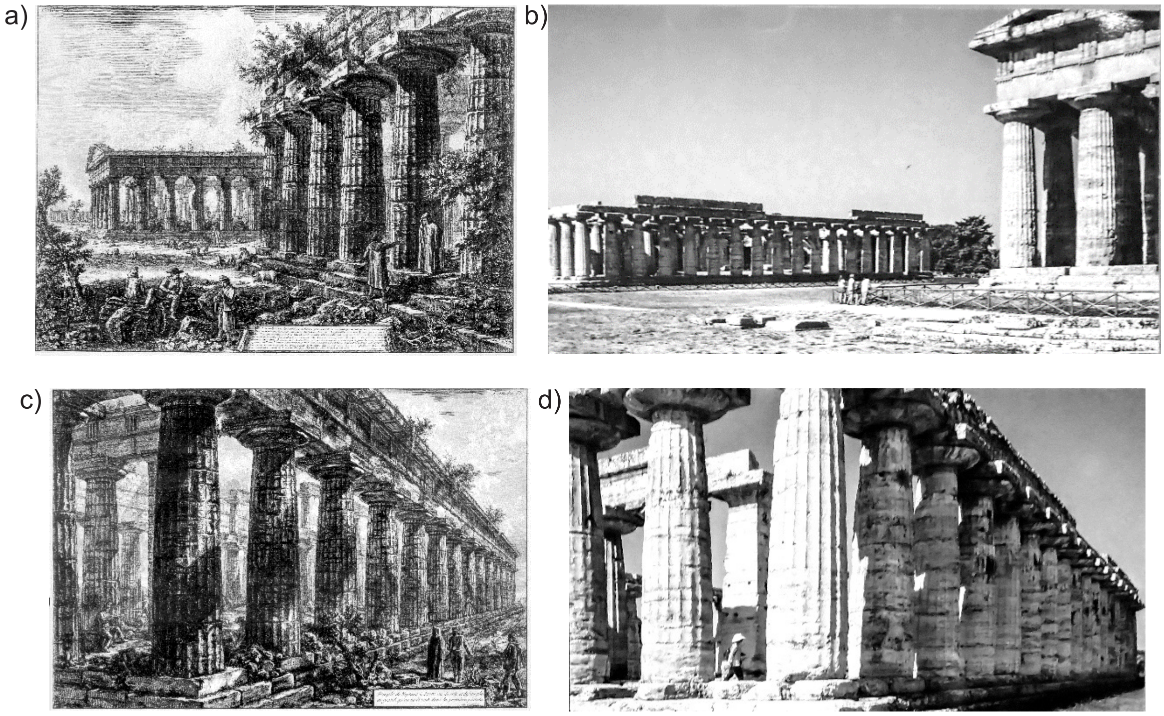


Figure 9. "Piranesi. Before and After. Italy–Russia. XVIII–XXI Centuries". Photos by Gianluca Baronchelli. Photography as a means of identification of peculiarities of compositional thinking of G. Piranesi and his son F. Piranesi through the example of the series "Views of Paestum": a) G. B. Piranesi. View of the columns at the Basilica facade. Sheet III. Etching, chisel, 502x680. Pushkin State Museum of Fine Arts, Moscow; b) Gianluca Baronchelli. Photograph, 2016; c) G. B. Piranesi. Temple of Neptune. Sheet XI. Etching, chisel, 460x690. Pushkin State Museum of Fine Arts, Moscow; g) Gianluca Baronchelli. Photograph, 2016

Conclusions

In his art, G. B. Piranesi developed and affirmed the accumulated experience of his predecessors and teachers, who had used angular perspective as an artistic tool of arrangement on the plane, necessary for architectural and artistic imaging. The artist elaborated the visual scenario of movement both on the plane and inside the space of the engraving. In some cases, he emphasized diagonal structural lines starting from the edges of the engraving, in other cases, applying contrast between vertical and horizontal directions, imparted a psychological tension to his work.

Results

The first comparative composition analysis of some sheets in series "Antique Vases, Candelabra, Tombstones, Tomb-Chests, Trivets, Braziers, and Ancient Carvings…" revealed a part of Piranesi's hornbook of spatial constructions.

The applied comprehensive analysis of Piranesi's architectural graphics was aimed at revealing the artist's method, which showed his striving for focused and consistent presentation of his artistic conception.

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EVOLUTION OF KREMLINS AS EVOLUTION OF RUSSIAN URBAN SETTLEMENTS

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Abstract

The Kremlin is considered to be the first stage of evolution of the urban settlement in the period of strengthening of the Russian centralized state. Five main functions of the kremlin were identified. By now, some functions of Kremlins have been transformed or replaced as a result of turning them into museums.

At the kremlin, the focus is harmoniously shifting from one function to another. The kremlin ensemble evolves with the urban settlement. Formation and development of Kremlins is a phenomenon of the world heritage, a starting point of unique Russian city formation. In order to introduce the concept of the “Russian Kremlin” as a phenomenon to the world community, its basic attributes and key definitions were determined. The current role of preserved kremlin complexes in municipal structures was estimated.

Keywords

Russian Kremlin, outstanding universal value, world heritage, evolution of the urban settlement

Introduction

In Russian cities, the kremlin has traditionally been the heart of all significant events in a settlement. A fortified center was a birthplace of the majority of Russian cities. Russian cities began their development from such fortified centers. Since any historical period requires proper city-planning decisions, the kremlin appeared as an independent fortified center in a Russian settlement and then developed as the main and the most fortified part of the city. It should be noted that many different people in different countries built fortresses to protect their lands from enemies, while the Russian Kremlin possessed purely defensive functions only at its initial development stages. From the very beginning of the Migration Period and due to some historical reasons, the East Slavs originally began to settle in territories starting with construction of fortified centers, which then became spiritual, craft, trade and economic, administrative and political centers of developing urban settlements and centers of residential areas, and only later on they appeared to be the main cores of cities in the modern sense of the term. The most important Kremlins became command and control centers of Russian ancient lands and principalities. As early as at the time of the Norman invasion of Europe, our land got the name “Gardarike”, which means a country of cities (fortresses) (Makovetsky, 2012a).

Each settlement was fenced around to defend it against robberies, invasions, and civil strives typical for the Middle Ages. A protected kremlin (a citadel, or a stronghold), the walls of which were the last obstacle to the enemy and the last protection for citizens, remained the basis of a developed settlement. Most cities had only one inner fortification in their structure, but further development made such a core only a part — although the main one — of a more advanced system of fortifications. It was natural for cities to protect its markets and residential suburbs with earthworks, palisades, and other defense lines. Some large cities eventually erected several rings of stone walls. As a rule, newly fortified parts of cities got their own names. For example, besides the Kremlin and big Zemlyanoy Gorod (earthworks town), Moscow included stone Kitay-gorod and Bely Gorod (White town); in different periods of history, Pskov fortress comprised several stone fortification lines: the Kremlin (Stronghold), the Dovmont Wall, the Wall of Posadnik Boris, the Middle Town, the Big Outer Town including fortified Zapskovye. In the first half of the XVII century, Astrakhan as a fortress consisted of the Kremlin, Bely Gorod (White town) and a small fortlet — a Granary. But in all cases a kremlin, a citadel, a stronghold remained a special area of a city endowed with a lot of responsibilities and specific functions, of which the defense function was gradually disappearing and put on a back burner. Pskov as a veche (people's assembly) city was particularly indicative, where the Kremlin (a stronghold) remained, above all, the spiritual and political, representative and administrative center of the republic city, and only then the military and defensive center (rather than a strategic place of storage of grain and weapons, and the last citadel). Residential, trade and craft functions gradually left the Stronghold for the peripheral areas of the city. After the loss of veche independence, memorial and spiritual functions of the Pskov Kremlin, remaining the historical, memorial and spiritual center ("House of the Holy Trinity") for the people of Pskov (Figure 1), became ever increasing.

Subject, objectives and methods

Starting at least from 1331, the kremlin has been mentioned in Russian chronicles under the term 'Kremnik' (citadel). Its etymology is examined within a semantic analysis of separate complexes (Khait, 2003). The central fortified part of the Russian medieval settlement had several older titles, such as "detinets" (citadel), "krom" (stronghold), "grad" (city) and some others. According to one of versions, the word "kremlin" came from the Greek 'κρημνός', which means "steepy". In the Middle Ages, hundreds of Kremlins were built in Russia. Unfortunately, only about 30 of them survived to the present day. Geographical layout of the most prominent representatives of surviving Kremlins is shown in Figure 2.

As it was noted at the 36th session of the World Heritage Committee of the UNESCO, they, without exaggeration, form "a constellation of Russian Kremlins" on the map.

The Russian Kremlin is a unique phenomenon in the city-planning architectural heritage; it is closely associated with formation and development of cities and all significant events in Russian history. This sententia is also recognized by the international community. As part of compliance with the Convention concerning the Protection of the World Cultural and Natural Heritage and the Operational Guidelines for the Implementation of the World Heritage Convention, the Moscow Kremlin, Novgorod Kremlin, Kazan Kremlin, and Suzdal Kremlin have already been put on the World Heritage List. They are marked with the biggest "stars" in Fig. 1. Such a mechanism of special status awarding to outstanding historical and cultural monuments is recognized as the most effective in

Figure. 1. Pskov Kremlin. General view of the Kremlin ensemble from the north side

Figure. 2. Location of kremlins on the historical map

the international practice. It should be noted that three of these Kremlins were nominated being a part of complexes of historic development, and only the Kazan Kremlin was nominated as an independent architectural ensemble. In 2010, the preliminary list of World Heritage Sites included special serial nomination “Russian Kremlins”, which at the present moment includes the most significant Russian monuments, i.e. the Astrakhan Kremlin, Pskov Kremlin, and Uglich Kremlin. Subsequently, as far as the monuments are ready and prepared and in accordance with the requirements of the ICOMOS and World Heritage Committee, the list is expected to be expanded and it is proposed to add to the serial nomination such significant and well-preserved monuments as the Nizhny Novgorod Kremlin, Tula Kremlin, Tobolsk Kremlin, and Zaraysk Kremlin following basic attributes and key definitions of the nomination. Previously nominated Kremlins are theoretically considered as phenomena, but there is no need to include them into the serial nomination, as they are already world heritage sites. Since all considered Kremlins possess outstanding individual features in addition to the common definition, then extension of the nomination would allow highlighting of the unique phenomenon of the world heritage.

Along with Russian Kremlins, some ensembles similar to them in architectural style, fortification principles, and space planning solutions have been preserved. These include urban fortresses, fortified monasteries, castles or fortified governmental (Alexandrovskaya village) and spiritual residencies (Rostov Kremlin). However, the most significant and characteristic features of this phenomenon are not in its external characteristics, but in functions inherent to kremlins. The main purposes of the fortress are accommodation of a military post, maintaining of its combat capability and strengthening of its defensive potential. The main purposes of the monastery complex are spiritual perfection, solitude for prayers, and refuge from the worldly life for inhabitants of the monastery. The main functions of the castle are residence of the governor, governor’s personal troops, administrative specialists and servants, and mandatory isolation from the surrounding dependent population. To different extents, these complexes reveal the above-mentioned elements of functions of Russian Kremlins, but, in contrast to kremlins, only one main function prevails in each of them. The Russian kremlin possesses multifunctionality and specific function that is not inherent to the fortified centers of the East or West. Originally, the Russian kremlin existed as a citadel for people of both the city and surrounding counties and administrative territories; it was a spiritual center and focus of power and its political attributes. We also cannot underestimate the role of the kremlin as a depot of strategic military and food supplies, the main memorabilia, art and spiritual things, documentary archives and commercial standards (the Armory Chamber, a treasury of the Moscow Kremlin, is a perfect example). The entire population of the city and vicinity hid and held the fort behind the walls of the Kremlin using it as the last public (!) hiding place in the event of external threats. This fact also distinguishes Kremlins from other similar complexes.

Results and discussion

In accordance with the postulates set forth, the main features characterizing Russian kremlins were outlined during preparation of the nomination “Russian Kremlins” and their inclusion in the World Heritage List (Makovetsky, 2012b). Three main functions of Russian kremlins named above were expanded with other functions that accompany the fundamental principle of the city. A full list of these features is presented in Table 1.

For centuries, Russian Kremlins performed their main functions. As a result, the kremlin was not only the city fortress, but also a specific central area of the city where governing bodies, churches with religious shrines, strategic reserves, as well as dwellings for the most important citizens and military posts were situated. The main feature of republic cities Novgorod and Pskov is that the military post and dwellings of civil administrators were not allowed to be located in citadels and strongholds. Thus, the kremlin functions depended on the features of the political regime.

The Kremlin was a city itself at the first stage of its evolution. Then, suburbs were constructed around it, as a rule. A trading and economic center of the settlement developed then near the walls of the kremlin. Suburbs developed along the road leading to the kremlin gate towers, meanwhile roads turned into the street network of the city development (Sevan, Ilvitskaya, 2005). Kremlins retained the function of the main city planning focus throughout the life of the city. And even nowadays, the kremlin in Russia is an ancient citadel, which historically outlined the main core and determined the structure of many Russian cities. Location of some kremlin ensembles in the territory of current municipalities is shown in Figure 3.

Some urban arrangements reveal a clear city planning role of the kremlin, while in other cases integration of the historic ensemble into the modern urban development is not always precise but balanced. The city and the Kremlin have always been inseparable and closely related. They have always been an integral unit. We can say that it was the Kremlin that defined the development structure of a future city. The most typical scheme of such development started with a cusp (sectorial) fortified settlement (a future kremlin). Then the development continued with sectorial suburb construction. Then it turned into a segmented development scheme, aiming for a circle arrangement. Evolution of such typical Russian city can be seen through the example of Veliky Novgorod, while the most complete version of such city is Moscow (its historic heart within the Garden Ring Road).

Kremlins have been continuously improved, even in the early days of their development. Since the 11th century, they were rebuilt in stone or brick, surrounded by gaps or moats, completed with fortification earthworks. As a rule, a Prince’s Palace, cathedrals, mansions of boyars and clergy of higher ranks, armories and granaries were built in the

Table 1
The main functional features of Russian kremlins

No.	Function	Expanded definition
1	Administrative (Political)	All forms of administrative management concentrated in the kremlin. Here, a voivode, a Governor’s representative, a writ hut consisting of religious and minor officials responsible for business correspondence and keeping of city archives were located; a court and a prison were also situated here.
2	Defensive	The kremlin had a key role as the city citadel. If the enemy moved beyond the outer fortification of the city, the entire population of the city and soldiers hid in the kremlin, where they held the fort. For this purpose, there were warehouses for weapons and supplies, barns for food and wells of fresh water in the territory of the Kremlin.
3	Religious	It was the religious center. Cathedrals of great beauty were built in the kremlin. Besides the main cathedral, several churches were built in many kremlins. It was very important for the spread of Orthodoxy in Russia. As for large kremlins, for example, Moscow, Astrakhan, Kazan and Kolomna kremlins, even monasteries were located in their territory.
4	Residential (settlement of people)	The kremlin had quite a lot of residential houses, especially in big cities, Moscow, Astrakhan, Kazan and Nizhny Novgorod Kremlins were severely overcrowded, especially in the 18th century. Houses of the most privileged citizens were located in the territory of the kremlin.
5	Commercial	Trading was insignificant inside the kremlin. Meanwhile, the city main market was located right next to it, outside of the walls of the kremlin. It took great areas, for example, the Red Square in Moscow.

Figure 3. Location of kremlin ensembles in modern urban development: a) Moscow; b) Pskov; c) Astrakhan; d) Suzdal; e) Kazan; f) Veliky Novgorod; g) Tula; h) Tobolsk; i) Zaraysk

Kremlin. The remaining Kremlins were developed or rebuilt in the 16th–17th centuries, mainly at locations of former earth-and-timber fortifications.

The most outstanding example of such development is the Moscow Kremlin. The place where the Kremlin was built had been known as the "City of Moscow" until the 14th century. The City was significantly expanded by Prince Yuri Dolgorukiy in 1156. In 1366–1368, Dmitry Donskoy replaced the oak works of the fortress with walls of white limestone. Along with strengthening of the Moscow Kremlin fortifications, in 1500–1511, the walls and towers of Pskov and Veliky Novgorod were also rebuilt and fortified. Final establishment of the single Old Russian state and external threats demanded a unified system of external defense that concentrated in Russian Kremlins. South-eastern approaches to Moscow were protected by powerful strongholds; one after another, stone Kremlins were built in Tula (1514–1521), Kolomna (1525–1531), Mozhaysk (1541), Kazan (1555), Serpukhov (1556). At the end of the 16th century, fortress cities, as outposts of the Russian state, were established on the Volga: Samara (1586), Saratov (1590), Tsaritsyn (currently Volgograd) (1589), Astrakhan (1558). Fortified settlements were developed in Siberia: Tyumen (1596), Tobolsk (1587), Tara (1594), Surgut (1504) and others. The final step was construction of the western Smolensk frontier (1597–1602).

Thus, during a short period of time, in the 16th century, a unified national system of kremlin complexes was established in Russia. It covered almost all lands, united into the Russian State by that time. The main feature of that time was construction of fortress Kremlins, which originally protected the entire perimeter of existed settlements (Smolensk, Nizhny Novgorod, Astrakhan). Russian Kremlins became the basis of the defense system, remaining active centers of city formation. This was one of the main factors, which combined all Kremlins into a single unit at that period. Formation and development of each kremlin is the most important component of historical formation of the Russian state.

Considering the above, it becomes clear that the concept of the "Russian Kremlin" has a multiple-meaning nature and has developed over centuries, changing its basic features and definitions. It should be noted that this multiple meaning sometimes allows researchers attributing other fortified centers and settlements to Russian Kremlins.

In order to show the world community the concept of the “Russian Kremlin” as a phenomenon, we established its basic characteristics and key definitions (Sheremetov, Lagunin, 2013). Nine key definitions and attributes of the concept “Russian Kremlin” were proposed, which correspond to notions of originality of this phenomenon and justify its outstanding universal value to the fullest extent possible. They are presented in Table 2. Kremlin ensembles that most clearly and vividly reflect certain basic attributes are also stated here, since only within the framework of a serial nomination outstanding features and different stages of development can be communicated to the fullest extent possible, confirming key definitions and disclosing key attributes of such amazing heritage site as the “Russian Kremlin”, common for Russia.

Remaining a cradle of the city, the kremlin was certainly positioned in different ways in different historical periods. Development not always resulted in strengthening of the attributes peculiar to the kremlin. If some of the defining features decayed, a complex ceased to correspond to the key attributes of the concept “Russian Kremlin”. For example, the Alexandrovsky Kremlin was transformed into a royal residence, while some other Kremlins were turned into residences for religious institutions.

In accordance with the definitions of the basic attributes established by the authors for Russian Kremlins that had the most distinctive development in the Russian State history and outstanding universal value for the world culture, as well as in accordance with the basic features inherent to these objects, the concept of “Russian Kremlin” is a fully characteristic of preserved complexes represented in Table 3. Here, the sign “!” marks the most vividly manifested attributes in stated Kremlin complexes. Not all other ensembles can be characterized by key definitions to the full. In some cases, these attributes had been lost over time, while others had not been developed. However, all preserved kremlin complexes without exception remain the “heart” of the city. Kremlin ensembles preserved in cities remain a focus of city planning in most of them and continue to play their role in the life of the settlement. Kremlins often form a structure of a social center being a site for various public events and a main sightseeing place in cultural tourism programs.

As it has been already mentioned, up to the present time, some functions of Kremlins have been transformed, and others have been substituted as a result of modern adaptation and turning them into museums. Data on transformations, as a rule, correlate to changes in the city development. Large-scale cultural events are held in Kremlins; various creative authors find here a site for implementation of their ideas. It can be clearly seen through the example of the Astrakhan Kremlin. Citizens have

Table 2
Key attributes and definitions of the concept “Russian Kremlin”

No.	Key definitions (attributes)	Most outstanding representatives
1	A center of origin of outstanding historical cities of ancient Russia, keeping the memory of a long history of an urban settlement starting from initial stages of its development; a monument of archeology and history, storing nonmaterial evidences and values.	Kremlins in Moscow, Pskov and Uglich
2	An original and unique in its structure central ensemble of an ancient Russian city; a prominent political, administrative and representative center of a historic city, preserving traces of different historical eras in its architecture and planning decisions.	Kremlins in Moscow, Pskov, Novgorod
3	Guardians of traces and monuments of international and interethnic cultural contacts in the Russian history.	Kremlins in Kazan and Astrakhan
4	A unique monument and achievement of original Russian and international art of fortification; a monument to the history of heroic defense of the Russian state.	Kremlins in Tula, Nizhny Novgorod and Astrakhan
5	An outstanding and holistic ensemble of stone architecture, preserving rare examples of national architecture, included into the anthology of the Russian architecture, and examples of mural, arts and crafts, and examples of original craftsmanship, use of traditional techniques and materials of local art schools.	Kremlins in Moscow, Astrakhan, Pskov and Uglich
6	Outstanding focus of city planning and the center of city planning structure merged with the natural landscape of a historical Russian city.	Kremlins in Tobolsk and Pskov
7	A historical ensemble of rare beauty and preservation in the landscape of an ancient Russian city and urban ensemble; an example of blending with the natural environment, landscape and historical buildings.	Kremlins in Moscow, Zaraysk and Astrakhan
8	A unique example of a memorial and sacred ensemble in the Russian city.	Uglich Kremlin
9	A spiritual Orthodox and sacred center of the Russian city, where outstanding temples, cathedrals, necropoles, and monuments of church architecture and archeology play a crucial role in an ensemble.	Kremlins in Suzdal and Novgorod

Table 3
Characteristics of kremlins complying with key attributes and definitions

No.	Name	Items of key attributes	Characteristics of the object
1	Moscow Kremlin	1(!), 2(!), 3, 4, 5(!), 6, 7, 8, 9	An outstanding and the most architecturally developed example of a metropolitan kremlin ensemble; it preserved not only the traces of centuries-old history but prominent ensembles of fortress, civil and church architecture, retaining the function of the main political center and symbol of the country.
2	Novgorod Kremlin	1, 2, 3, 4, 5, 6, 7, 8, 9(!)	An outstanding ancient ensemble of a metropolitan kremlin of the Novgorod Republic; it was rebuilt in brick after the republic was joined to the unified centralized state. It preserved in its ensemble prominent monuments of architecture and art such as the cathedral church of St. Sophia (mid XI century) and the monument "Millennium of Russia" as a symbol of one of the first capitals of the ancient Russia (1862).
3	Suzdal Kremlin	1, 2, 3, 4, 5, 6, 7, 8, 9(!)	Kremlin of the capital of one of the most ancient Russian principalities; it preserved such monuments as the Cathedral of Nativity of the Theotokos built in the XII century and Archbishop's Chambers of the XV–XVII centuries.
4	Kazan Kremlin	1, 2, 3(!), 4, 5, 6, 7, 8, 9	An outstanding frontier fortress kremlin built in the middle of the XVI century in the former capital of the Kazan Khanate; it possesses the cathedral complex, traces and monuments of the history of two national cultures.
5	Pskov Kremlin	1, 2, 3, 4, 5(!), 6(!), 7, 8, 9	A complex of the VIII–XIX centuries; it preserved archaeological monuments and traces of a 1100 year-old history of the city, unique structures of the capital veche center typical for Russian cities, including a temple ensemble of the Dovmont city (archaeological monument in the open air). A prominent beautiful architectural ensemble in the landscape of the historical city blending with the natural environment.
6	Uglich Kremlin	1, 2, 3, 4, 5(!), 6, 7, 8(!), 9	A complex of the X–XVII centuries. An example of an earth-and-timber fortification that survived several construction phases and preserved an ensemble of sacred and memorial stone buildings, including the oldest in Russia preserved Appanaged Princes' Palace", the Church of Tsarevich Dmitry on the Blood (XVI century), built on banks of the Volga where the last legitimate heir to the throne, the son of Ivan the Terrible was killed (1592). Here, remarkable ensembles of wall paintings, including those dedicated to local events, retained.
7	Astrakhan Kremlin	1, 2, 3(!), 4, 5, 6, 7(!), 8, 9	A complex of the XVI–XVII centuries – beginning of the XX century. A fortress kremlin of the final period of development of Russian fortress architecture with outstanding fortress facilities remained in the full ensemble, including military constructions of the XIX century. Cathedrals of the Kremlin ensemble include a prominent example of Russian baroque — the Cathedral of the Assumption with a unique adjoining elevated circular platform of the Lobnoye Mesto (the Place of Execution).
8	Nizhny Novgorod Kremlin	1, 2, 3, 4(!), 5, 6, 7, 8, 9	A kremlin of the XIV–XVI centuries. A well-preserved multi-towered ensemble of one of the major fortress kremlins on the Volga; it had lost its strategic significance after the conquest of Kazan. Stone construction started in the end of the XIV century.
9	Zaraysk Kremlin	1, 2, 3, 4, 5, 6, 7(!), 8, 9	A complex of the first quarter of the XVI century. One of the most well-preserved stone kremlins with seven towers and three gates. It preserved cathedrals dating to the end of the XVII century and the beginning of the XX century, an administrative building and the building of a religious school of the XIX century.
10	Tula Kremlin	1, 2, 3, 4(!), 5, 6, 7, 8, 9	XVII century. It has a unique location, being hidden in a valley of the countryside; the stone Tula Kremlin was the main fortified center of the Zasechnaya cherta (Great Abatis Border) and the most combative southern fortress of the Russian state.
11	Tobolsk Kremlin	1, 2, 3, 4, 5, 6(!), 7, 8, 9	An ensemble dating back to the end of the XVII century. A well-preserved ensemble of one of the latest built kremlins and the most easterly situated stone kremlin in Russia; it was built after the conquest of the Siberian Khanate. It has a wonderful location in the natural and historical landscape of the city.

already accustomed to Days of Russian Literature, New Year and Maslenitsa festivities traditionally held in the territory of the Kremlin, and in September 2012 they were going to the first-night. As a result of five-year rehearsals at the cathedral square, the Astrakhan State Theatre of Opera and Ballet presented a new production — the opera "Boris Godunov" by Modest Mussorgsky. The choice was not at all accidental. Prior to ascending to the throne, Boris Godunov was the governor of the Astrakhan Kingdom. This spectacular cultural event once again reminded of the historical fact that the Astrakhan Kremlin acquired its stone appearance which remained till our days during ruling of this governor. The Astrakhan Kremlin became the most perfect defensive building of the Moscow State. The area of the Kremlin allowed hiding all citizens behind its strong walls in the event of an enemy attack. Performing the function of the city, where population dwelled, the Kremlin had great social significance and was closely interconnected with surrounding settlements. Here, all administrative structures concentrated, and a local representative of the ruler, a voivode, had a residence (Sheremetov, Levitan, 2013).

Taking into account current development of communication technologies, we can estimate attitudes of the population to such an important — from the historical point of view — object as the kremlin ensemble by studying responses of the Web community. The project “Russia 10” which launched online in March 2013 demonstrated interest of citizens to kremlin complexes (http://10russia.ru). The ensemble of the Pskov Kremlin confidently entered the Top Ten during the nationwide votes; earlier the Kremlin had acquired the brand of the ancient Hanseatic Pskov. All this is fully consistent with principles of the UNESCO reflected in Chapter I.C of the Guidelines for the Implementation of the World Heritage Convention. According to Clause 15m, the Parties to the Convention commit themselves to “use educational and information programs to strengthen appreciation and respect by their peoples of the cultural and natural heritage”.

A complex mechanism of interaction of the historical and cultural complex with a modern municipality assumes some feedback. Not only the Kremlin meets the needs of the city, but also the society takes care of the Kremlin. Authorities of constituent regions and municipalities, as a rule, tend to coordinate their programs aimed at preserving monuments with government agencies and “giving the heritage a function in the life of the community”, according to Clause 15b of Chapter I.C of the Guidelines for the Implementation of the World Heritage Convention. The Ministry of Culture of the Russian Federation (http://mkrf.ru/)developed the Plan of administrative and financial activities within the framework of the federal target program “Culture of Russia (2012–2018)” which was approved by Order No. 88 of the Ministry of Culture of the Russian Federation (http://mkrf.ru/) as of February 5th, 2013. The program covers designing and restoration of kremlin complexes in Pskov, Porkhov, Tula, Astrakhan, Ryazan, Veliky Novgorod and other similar objects (http://mkrf.ru).

Conclusions

Thus, the Kremlin is a cornerstone of evolution of Russian urban settlements. Being a fundamental principle, it defined the planning structure of a future Russian city. The Kremlin defined the administrative status of a settlement. The Kremlin promoted development of trading and, therefore, prosperity of settlements, providing security. All important aspects of development and life of the city strengthened under the influence of the kremlin. The kremlin became a starting point of evolution of the urban settlement. And till now it remains the historic center of the city. Kremlin complexes with appropriate key attributes and definitions retained their role in the lives of urban population with account for current trends. For example, fortification elements of complexes were turned into museums or transformed into memorial objects attracting not only researchers but also other population groups. Some functions (such as city planning, representative functions, role of spiritual and administrative center) persist up to date in some cases. The Kremlin is enriched by cultural tourism components meeting today’s needs. Throughout the history, Kremlins changed together with the city. Developing together with the urban settlement, some of their functions transformed into another ones harmoniously. Formation and development of Kremlins is a phenomenon of the world heritage and a counterpoint to the unique Russian city formation.

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ASSESSMENT OF SEISMIC INPUT ENERGY BY MEANS OF NEW DEFINITION AND THE APPLICATION TO EARTHQUAKE RESISTANT DESIGN

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Abstract

A methodology for assessing the seismic input energy into structure (building) from earthquake (or seismic) excitation is proposed. The procedure is based on the energy balance of the structure and employs the earthquake intensity characteristic known as the specific energy density (SED) to estimate the maximum input energy. This energy is evaluated for the portion of earthquake record (accelerogram) where strong ground motion occurs (the interval between 5-95% accumulations of the Arias intensity). Comparison of the proposed approach in this paper and other proposals for assessing seismic input energy as a basis for energy-based seismic design methodology is presented. Since a critical condition to realize an energy-based seismic design is that the structure should have a rational relationship between damage/energy absorbed, the procedure establishes a relation between the seismic input energy into structure and strain, total cyclic displacement and low cycle fatigue. Seismic input energy obtained using this procedure is compared with results from other methods for assessment of seismic input energy. The procedure can useful especially, at the initial stage of design to provide the desired ductility to structure since it allows for evaluating the maximum input energy into structural system from any seismic excitation without recourse to dynamic analysis.

Keywords

Energy-based method, displacement, low-cycle fatigue, seismic excitations, seismic input energy, strain

Introduction

In most cases, seismic design practices structures are based on representing the earthquake loading effect in terms of static equivalent forces that are calculated from elastic response spectra relating the peak ground acceleration (*PGA*) with the absolute pseudo-acceleration response implemented in several current seismic codes. This procedure indirectly attempts to account for inelastic behavior during severe seismic excitation and the overstrength of the structure through ductility-based force-reduction factor, *R.* Based on these understanding, Fajfar (1992), proposed a methodology in which the ductility of the structure is reduced by a non-dimensional parameter γ that represents a normalization of the dissipated hysteretic energy E_{H}. Teran-Gilmore and Jirsa, (2005) used the observed correlation between the plastic energy demand E_{H} and the strength reduction factor *R* to propose two procedures for seismic design against low-cycle fatigue.

The force-based method has a number of disadvantages, which are outlined by Priestley *et al*. (2007). One of such disadvantages is that the earthquake loading effect depends on the elastic and plastic characteristics of the structure, which in turn govern the structural resistance. This relationship between earthquake loading effect and structural resistance makes seismic design cumbersome. In addition, the concept of equivalent ductility allows only implicitly to address the cumulative damage (low cycle fatigue) and is dependent on series of empirical parameters. Furthermore, the degree of protection against damage provided by force-based design methods under a given seismic intensity is non-uniform from structure to structure.

Since the 1990s, more emphasis has been laid on displacement considerations, resulting in the development of displacement-based design methods (Priestley *et al*., 2007). The maximum relative displacement is the structural response index often used for evaluating the inelastic behaviour of structures. However, it is widely recognized that apart from maximum displacement, the level of structural damage from seismic excitation depends on the cumulative damage resulting from numerous inelastic cycles (Fajfar and Vidic, 1994).

Recent earthquake excitations such as 2005 Kashmir earthquake in India, 2008 Sichuan earthquake in China, 2011 Fukushima earthquake in Japan and most recently the Central Italy earthquake of 2016 have imposed severe damage to relatively new buildings (structures) across several cities, designed based of some force- or displacement-based methods. These damages may in part be due to construction and design errors, and or partly due to the shortcomings of the employed seismic design method (code). If the latter is the case, it is a further confirmation that force-based design and displacement-based design does not result in reliable structural seismic design of building systems.

Serious consideration of seismic energy as an alternative index to other response quantities such as force or displacement earthquake resistant design began in 1950s. Since the original works by Housner (1956), Berg and Thomaides (1960), Kato and Akiyama (1975) and Housner and Jennings (1977), the energy-based procedure has been widely developed Zahrah and Hall (1984), Akiyama (1985), Kuwamura and Galambos (1989), Unag and Bertero (1990), Fajfar *et al*. (1992), McCabe and Hall (1989), Zhu and Tso (1992). Anderson and Bertero (2006) have given a review on the evolution of the energy-based method.

The fundamental basis of the energy-based seismic design (EBSD) is that, unlike the force-based and displacement-based methods of earthquake resistant design, is that the loading effect of seismic excitation on structures can be interpreted not as forces or displacements separately, but rather as the product of both, in terms of input energy E_{I}. A design approach based on energy, has the potential to address the effects of the duration, frequency content and hysteretic behaviour directly Khashaee *et al.* (2003). It must be noted, however, that the loading history also affects cumulative damage as discussed by several authors some of which include Benavent_Climent (2007); Chai (1995, 2004), Erberik and Sucouglu (2004), Sucouglu and Erberik (2004) in the context of both steel and reinforced concrete structural elements.

A basic parameter for the implementation of energy-based concepts is the estimation of the input energy that is considered a reliable indicator of ground motion severity. Accurate estimation of the seismic input energy from seismic excitation is therefore, very important. Researchers have used different earthquake strong-motion parameters for characterization of seismic hazard Safac (2000), Chou and Uang (2000), Ambraseys and Douglas (2003), Decanini and Mollaoli (1998, 2001), Benavent-Climent et al. (2002), Teran-Gilmore and Jirsa (2007), Amiri et al. (2008), Shiwua (2014), Rutman and Shiwua (2015). This has resulted in the proposal of strong-motion attenuation relationships, design energy input spectra and various formulations for representing the seismic demand with reference to single-degree-of-freedom (SDOF) systems.

In an energy-based seismic design, one needs to estimate the input energy in a structure and distribute it to various structural components. The development of an effective and feasible procedure for analyzing and evaluating the seismic demands is one major challenge in energy-based seismic design of structures. This paper seeks to offer an alternative procedure for assessing the seismic input energy into structural system based on energy considerations. The proposal employs the earthquake intensity characteristic known as the specific energy density (SED) to estimate the maximum input energy and establishes a relation between the seismic input energy into structure and strain, total cyclic displacement and low cycle fatigue.

Materials and method

The materials and methods used include proven research work by authors on the subject of energy-based seismic design, theory of seismic stability, general assumptions of structural mechanics, theory of elasticity and plasticity, earthquake records in the form of accelerogram and computer software like *Nonlin, SeismoSignal and Ing+*.

Existing procedures for computing input energy

Several methods have being proposed for estimating seismic input energy. However, only a select few will be examined for comparison within the context and limitations of this work.

Housner (1956) has presented a first estimation of the input energy per unit mass, based on the maximum kinetic energy, for both elastic and inelastic behaviour as:

$$E_{\mathrm{I}}/m = \tfrac{1}{2}(PSV)^2 \qquad (1)$$

where *m* is the mass and *PSV* denotes the pseudo-spectral velocity.

Akiyama (1985) proposed the input energy per unit mass for an elastic SDOF structure as:

$$E_{\mathrm{I}}/m = \tfrac{1}{2}(V_{\mathrm{E}})^2 \qquad (2)$$

where V_E (in *m/s*) is an equivalent velocity. He recommended the following values for V_E

$$V_{\mathrm{E}} = 2.5T \text{ for } T \le T_{\mathrm{G}};\ V_{\mathrm{E}} = 2.5T_{\mathrm{G}} \text{ for } T \ge T_{\mathrm{G}} \qquad (3)$$

where T is the period of the system, T_G is the predominant period of ground motion as a function of soil type. The values of T_G are 0.4, 0.6, 0.8, and 1.0 s for soil types I (bedrock), II, III, and IV (softest soil), respectively.

Kuwamura and Galambos (1989) used the equation proposed by Akiyama and recommended the following values for V_E

$$E_{\mathrm{I}}/m = \tfrac{1}{2}(V_{\mathrm{E}})^2$$

$$V_E = 0.5\sqrt{I_{\mathrm{E}} T_{\mathrm{G}}} \text{ for } T \geq T_G;$$

$$V_E = 0.5\sqrt{I_{\mathrm{E}}/T_{\mathrm{G}}}\,T \text{ for } T \leq T_G \tag{4}$$

where $I_{\mathrm{E}} = \int_0^t \ddot{u}_g^2 dt$ is the integral of the square of the ground acceleration for the total duration of accelerogram *t*.

Uang and Bertero (1990), proposed two different approaches to estimate the input energy, based on either the absolute or the relative equation of motion. Chopra (1995), and Bruneau and Wang (1996) believe that the input energy in terms of the relative motion is more meaningful than the input energy in terms of the absolute motion since internal forces within a structure are computed using relative displacements and velocities. The relative input energy per unit mass is defined as:

$$E_{\mathrm{I}}/m = -\int_0^t \ddot{u}_g \dot{u} dt \tag{5}$$

where $\dot{u}$ is the velocity of the mass relative to ground and $\ddot{u}_g$ is the ground acceleration.

Rutman (2012) proposed a formula that establishes the relation between the possible maximum seismic energy received by the system, and the criterion of cumulative absolute velocity (CAV). The proposal is generalised and does not depend on the degrees of freedom of a system, and on the presence of nonlinearities. This estimate is given as:

$$E(t)_{\mathrm{B}} \leq \tfrac{1}{2} m (CAV)^2 \tag{6}$$

where $E(t)_{\mathrm{B}}$ the seismic input energy into a system, $CAV = \int_0^t \left|\ddot{X}(\xi)\right| d\xi$ is the cumulative absolute velocity, $\ddot{X}$ is the ground acceleration.

Shiwua (2014) has applied Arias intensity to assess the seismic energy. The evaluation of the input energy per unit mass, taking into account only the nature of the impact is expressed as:

$$E_I/m = \tfrac{1}{2}\left(I_{\mathrm{A}}\right)^2 \tag{7}$$

where $I_A = \frac{\pi}{2g}\int_0^t \ddot{u}_g^2(t)\,dt$ is Arias intensity.

Background on energy-balance equation

The equation of motion of an inelastic single-degree-of-freedom system (SDOF) subjected to a unidirectional horizontal ground motion can be written as follows:

$$m\ddot{u} + c\dot{u} + F(u,\dot{u}) = -m\ddot{u}_g \tag{8}$$

where *m* is the mass, *c* is the damping coefficient, $F(u)$ is the restoring force, *u* is the relative displacement of mass, $\dot{u}$ is velocity of mass relative to base (first derivative with respect to time), $\ddot{u}$ is the acceleration of mass relative to base (or second derivatives with respect to time), $\ddot{u}_g$ is the ground acceleration.

Dividing all terms by the mass *m*, the Eq. (8) can be written in the form:

$$\ddot{u} + 2\xi\omega\dot{u} + f\left(u,\dot{u}\right) = -\ddot{u}_g \tag{9}$$

where $\xi = c/2\omega m$ is the dimensionless damping ratio, *ω* is natural frequency of the system, $f\left(u,\dot{u}\right)$ is the restoring force per unit mass.

Multiplying (8) by $du = \dot{u}dt$ and integrating over the entire duration of the earthquake give the energy balance equation

$$E_{\mathrm{K}} + E_{\xi} + E_{\mathrm{A}} = E_{\mathrm{I}} \tag{10}$$

where $E_{\mathrm{K}} = \int_0^t \dot{u} m \ddot{u} dt = \frac{1}{2} m\dot{u}^2$ is the relative kinetic energy, $E_{\xi} = \int_0^t c\dot{u}^2 dt$ is damping energy, $E_A = \int_0^t F(u,\dot{u})\dot{u}dt$ is the absorbed energy and $E_{\mathrm{I}} = -\int_0^t m\ddot{u}_g \dot{u} dt$ is the relative input energy. The absorbed energy comprises of the recoverable elastic strain energy, E_{S}, and the energy dissipated through plastic deformation (irrecoverable hysteretic energy), E_{H}, that represents the cumulative damage to the structure, i.e. $E_{\mathrm{A}} = E_{\mathrm{S}} + E_{\mathrm{H}}$ and Eq. (10) is rewritten as:

$$E_{\mathrm{K}} + E_{\xi} + E_{\mathrm{S}} + E_{\mathrm{H}} = E_{\mathrm{I}} \tag{11}$$

The left-hand side of equation (11) describes the ultimate energy absorbing capacity (UEAC) while the right-hand side of the equation represents the loading in terms of input energy into a structure from earthquake excitation. Seismic stability of the structure can be evaluated by comparing the expected value E_{I} at the site where the structure is located, with the value of UEAC (Benevant-Clement and Zahran, 2010). At the brink of collapse, the UEAC and E_{I} have the same value; therefore the seismic capacity of building can be expressed in terms of the E_{I} corresponding to the “ultimate earthquake” that the building can resist.

On the other hand, the sum of E_{K} and E_{S} constitutes the elastic vibrational energy of the system, E_{E}. So that equation (11) can be rewritten as:

$$E_{\mathrm{E}} + E_{\mathrm{H}} = E_{\mathrm{I}} - E_{\xi} \tag{12}$$

The difference between E_{I} and E_{ξ} is considered the energy input that contributes to damage E_{D} by Housner (1956).

$$E_{\mathrm{D}} = E_{\mathrm{I}} - E_{\xi} \tag{13}$$

At the end of the ground motion duration E_{E} is almost zero; consequently, from Eqs. (12) and (13) it follows that E_{H} can be taken as equal to E_{D}, i.e. $E_{\mathrm{H}} \approx E_{\mathrm{D}}$. Further, E_{I} and E_{D} can be normalized by the mass m and expressed in terms of equivalent velocities V_{E} and V_{D} defined by:

$$V_{\mathrm{E}} = \sqrt{2E_{\mathrm{I}}/m};\ V_{\mathrm{D}} = \sqrt{2E_{\mathrm{D}}/m} \tag{14}$$

Numerical analysis of the inelastic response under earthquakes shows that the seismic input energy, E_{I}, is mildly affected by the strength; is insignificantly affected by the configuration of the restoring force characteristics of the structure and scarcely affected by the fraction of critical damping ξ. The ratio, E_I/m, is independent of the total mass *m* of the structure and mainly dependent on the vibration periods T_i of the structure, mostly on that of the first mode T_1 (Zahrah and Hall,1984; Akiyama, 1985; and Kuwamura and Galambos, 1989).

Procedure for estimation of seismic input energy into SDOF system during earthquake

When the structure enters the inelastic range, there is a deterioration of the hysteretic behaviour, which can lead to failure of critical elements at deformation levels significantly below the ultimate deformation capacity of the structure. Therefore, of particular interest is the dissipated hysteretic energy, E_H, which is the structural response parameter that is commonly correlated to cumulative damage, and it provides a good characterization of the severity of plastic cycling (Teran-Gilmore and Jirsa, 2005). Due to the monotonicity of E_H, the evaluation, of its maximum value must be done at the end of seismic excitation or at the end of the intensive phase of excitation ($\bar{t}$).

Numerical analysis shows that the term $E_\xi = \int_0^t c\dot{u}^2 dt$ in Eqs.(10) – (12) for a SDOF system (Fig. 1) can be neglected due to its smallness. Integrating $\int_0^t \ddot{u}_g \dot{u} dt$ by parts results to the following expression:

$$E_{\mathrm{I},1} = \int_0^{\bar{t}} \ddot{u}_g \dot{u} dt = \dot{u}_g \dot{u}\Big|_0^{\bar{t}} - \int_0^{\bar{t}} \dot{u}_g \ddot{u} dt = -\int_0^{\bar{t}} \dot{u}_g \ddot{u} dt \qquad (15)$$

where $E_{\mathrm{I},1}$ is input energy per unit mass.

By neglecting viscous damping from Eq. (8) or (9), it follows that

$$\ddot{u} = -f(u,\dot{u}) - \ddot{u}_g \qquad (16)$$

By substituting Eq. (16) into (15), we obtain:

$$E_{\mathrm{I},1} = \int_0^{\bar{t}} \ddot{u}_g \dot{u} dt = \int_0^{\bar{t}} \dot{u}_g \Big(f(u,\dot{u}) + \ddot{u}_g(t) \Big) dt =$$

$$= \int_0^{\bar{t}} \ddot{u}_g \dot{u}_g dt + \int_0^{\bar{t}} f(u,\dot{u}) \dot{u}_g dt$$

$$= \frac{\dot{u}_g{}^2}{2}\Bigg|_0^{\bar{t}} + \int_0^{\bar{t}} \dot{u}_g f(u,\dot{u}) dt = \int_0^{\bar{t}} \dot{u}_g f(u,\dot{u}) dt \qquad (17)$$

At the end of the ground motion duration E_E is almost zero; consequently, from Eqs. (12) and (13) it follows that E_H can be taken as equal to E_D, i.e. $E_\mathrm{H} \approx E_\mathrm{D}$. Given that $\dot{u}_g(\bar{t}) = 0$ and taking into account Eq. (17), we obtain the following expression from (12)

$$E_{\mathrm{H},1} \le \int_0^{\bar{t}} \left| \ddot{u}_g \dot{u} \right| dt = \int_0^{\bar{t}} \left| \dot{u}_g f(u,\dot{u}) \right| dt \qquad (18)$$

where $E_{\mathrm{H},1}$ is hysteretic energy per unit mass.

Let us introduce the following notation

$$\left| f(u,\dot{u}) \right| = f_{\max} \qquad (19)$$

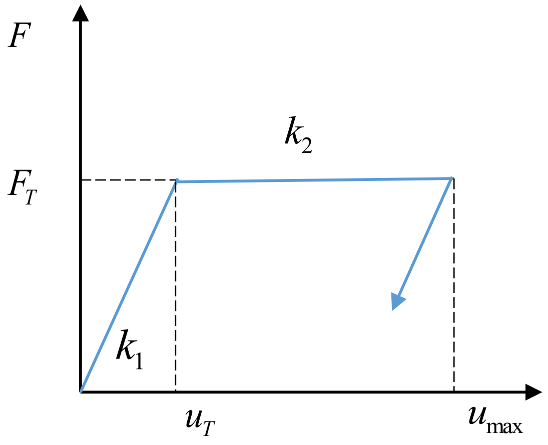

Figure 1. Elastic perfectly plastic (Elastoplastic) system

Using Eqs. (18) and (19) and applying the Cauchy-Schwarz inequality we obtain:

$$E_{\mathrm{H},1} \le f_{\max} \sqrt{\bar{t} \int_0^{\bar{t}} \dot{u}_g{}^2 dt} \qquad (20)$$

where $f_{\max}$ is the lateral yield force, $\bar{t}$ in the time corresponding to the duration of strong ground motion (Fig. 2). The integral $\int_0^t \dot{u}_g{}^2 dt$ is referred to as the *Specific Energy Density* of earthquake. In this case, the SED value is determined for an interval of the duration of earthquake motion $\bar{t}$ corresponding to the significant duration and defined as $\int_0^{\bar{t}} \dot{u}_g{}^2 dt$.

Equation (20) can be expressed as:

$$E_{\mathrm{H},1} \le f_{\max} \sqrt{\bar{t} SED} = E_{\mathrm{SED}} \qquad (21)$$

where E_{SED} is the seismic input energy per unit mass based on SED.

Transition from energy loading of system to level of deformation during elastoplastic cyclic loading

A relationship between the input energy demand and the maximum displacement of structure

The diagram shown in Figure 3 schematically represents typical shear drift curve, $f - \Delta$, of a given SDOF system (building) subjected to seismic actions.

The values $\left| f(u,\dot{u}) \right|$ and Δ_i are the corresponding values at yielding. The integration of the $f - \Delta$ curve i.e. linear summation of the displacements at different stages of cyclic deformation, gives the hysteretic energy dissipated by the system, E_H, which represents the cumulative damage in that storey (or building).

Following the notation in Figure 3, we obtain:

$$E_{\mathrm{H},1} = f_{\max} \sum_{i=1}^{z} \left| \Delta_i \right| \qquad (22)$$

where Δ_i is cyclic displacement corresponding *i*-th cycle, *z* is the number of half cycles.

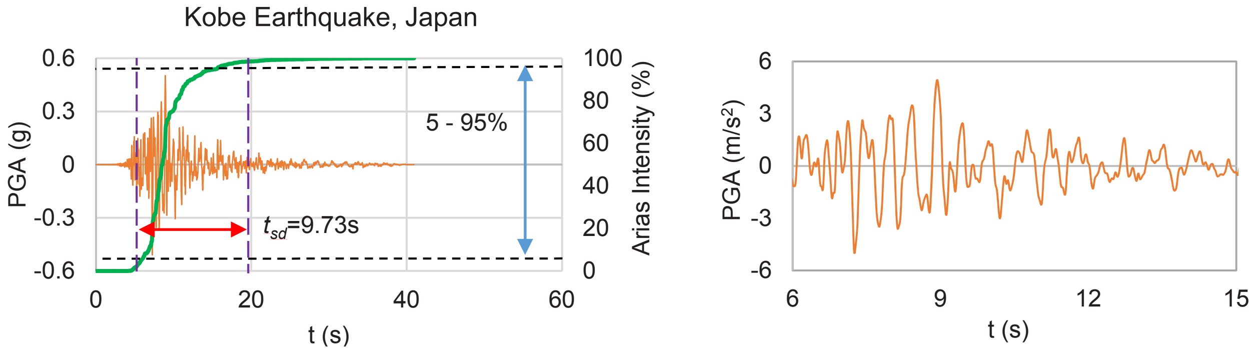

Figure 2. Interval of the strong motion on the example of Kobe earthquake record, Japan

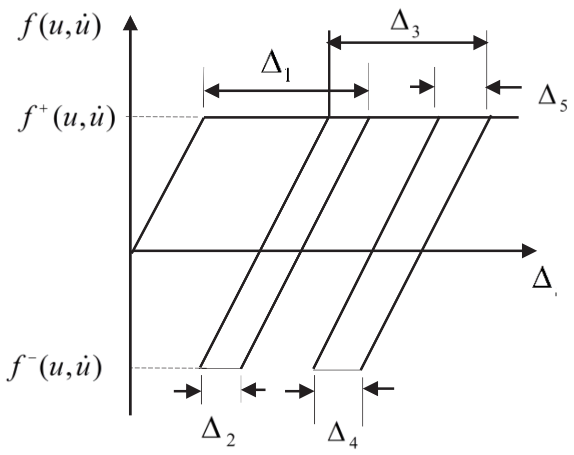

Figure 3. Cyclic stress-strain diagram

From equations (21) and (22) we obtain:

$$f_{\max}\sum_{i=1}^{z}|\Delta_i| \le f_{\max}\sqrt{tSED} \tag{23}$$

This way is the total displacement of the system with single degree of freedom is expressed as:

$$\sum_{i=1}^{z}|\Delta_i| \le \sqrt{tSED} \tag{24}$$

The left hand side of the inequality (24) is considered (within the framework of the above assumptions of using a model with single degree of freedom) as the total cyclic displacement of the top of the structure. If a relationship between displacement and deformation is established, the relation (24) allows determining the possibility of low-cycle fracture.

Relationship between deformation and displacement

Usually, in order to simplify analysis beyond the elastic limit, strain (deformation) curves are schematized. A common variant of this schematization is the stress-strain exponential relationship given as:

$$\sigma = \bar{B}_1|\varepsilon|^{\mu-1}\varepsilon \tag{25}$$

where σ – stress, ε – strain, $\bar{B}_1$ characteristic parameter for the considered material, μ is strain hardening parameter, $\bar{B}_1 > 0$ and $\mu \le 1$ are constants.

Applying the stress-strain exponential relationship leads to following relation:

$$\bar{B}_1 J_{\text{ob}}|\chi|^{\mu-1}\chi = -M \tag{26}$$

where $\chi = d^2v/dx^2$ is the curvature of the beam, J_{ob} is the generalized moment of inertia.

Figure 4 shows the stress dependence on the index η due to beam bending. Plastic deflection for a cantilever shown in Figure 5 (Simbort, 2012) is defined as follows:

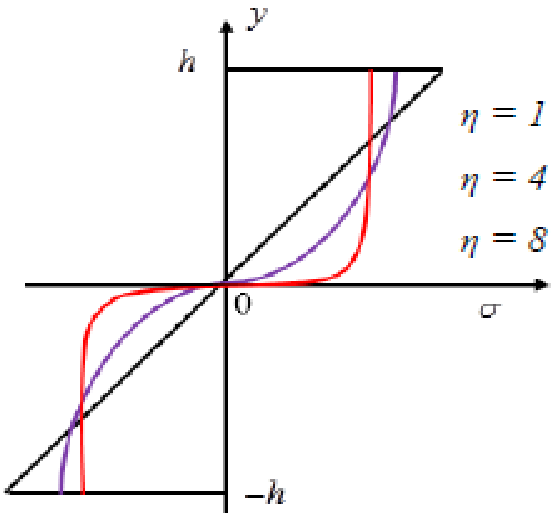

Figure 4. Relationship between the parameter η and stress distribution under bending

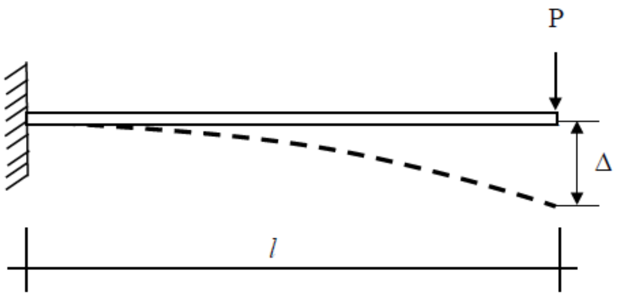

Figure 5. Deflection of cantilever beam

$$\Delta=\frac{P^{\eta}l^{2+\eta}}{(2+\eta)D} \qquad (27)$$

where $\eta=1/\mu$, $D=\bar{B}_1^{\eta}J_{\text{ob}}^{\eta}$, P point load at the end of the beam, and *l* is the length of the beam.

Applying the recommendations of Simbort (2012) to Eqs. (26) and (27) result in the following relationship between deformation (strain) and displacement

$$\Delta=\frac{M^{\eta}l^{2}}{(2+\eta)D}=\frac{\left[\bar{B}_1 J_{\text{ob}}\left(\frac{\varepsilon}{h}\right)^{\mu}\right]^{\eta}l^{2}}{(2+\eta)D}=$$

$$=\frac{\bar{B}_1^{\eta}J_{\text{ob}}^{\eta}\frac{\varepsilon}{h}l^{2}}{(2+\eta)\bar{B}_1^{\eta}J_{\text{ob}}^{\eta}}=\frac{\varepsilon l^{2}}{h(2+\eta)} \qquad (28)$$

By making the strain in Eq. (28) the subject of the formula, we obtain

$$\varepsilon=\frac{h\,(\Delta)}{l^{2}}(\eta+2) \qquad (29)$$

where *h* is height of beam section.

Figure 6 is used to describe one of the possible ways of establishing a relationship between top displacement of structure and the maximum deformation. Often, in framed buildings structures, the weakest is the lower (first) storey. The lower storey is weakened for functional reasons: the presence of many shops, public facilities and open spaces, etc., so there are less load-bearing columns. At the same time, the maximum load acts on the lower floor (storey). During transition to limit equilibrium state, plastic hinges are formed only at the lower storey. Therefore, the displacement of the top of the building coincides with the displacement of the ground floor beam.

In this case, considering the bending moment diagram of columns, the bending moment at the middle is equal to zero. The column behaves as two identical, sequentially, connected beams, with plastic hinges at the rigid supports. Based on the above assumption, a transition to the problem of determining the maximum stresses in the elastoplastic cantilever beam with free end displacement is achieved. As shown in Figure 6b, the displacement of the free end of the equivalent cantilever beam is equal to half the displacement of the lower (first) storey beam (floor) and consequently, the top of the building.

The resulting Eq. (29) for cantilever beam can be used to determine the maximum plastic deformations in the structural elements, in particular, in frame elements of buildings.

By following the recommendations of Simbort (2012), it is possible to determine the position plastic hinges (Figure 6a) due to limit load and reduce (or convert) the analysis to the design of cantilever beams.

To achieve this it necessary to

I. Geometrically, link the top displacement of the structure (established upon evaluation of the input seismic energy) to the floor drift of each storey (frame contour).

II. Transit from the floor displacement of each storey to displacement of an equivalent cantilever beam as shown in Figure 6b (at the middle of the column, moment is zero, so its half behaves like a cantilever beam).

III. Use Eq. (29) to determine the maximum deformation in the lower rigid supports of the frame where plastic hinges are formed.

The location of plastic hinges can be determined, by performing limit equilibrium analysis where the horizontal load is proportional to the distributed mass of the system by method of pseudo-rigidity proposed by Routman (1997), and realized in the computer program “**Ing+**”.

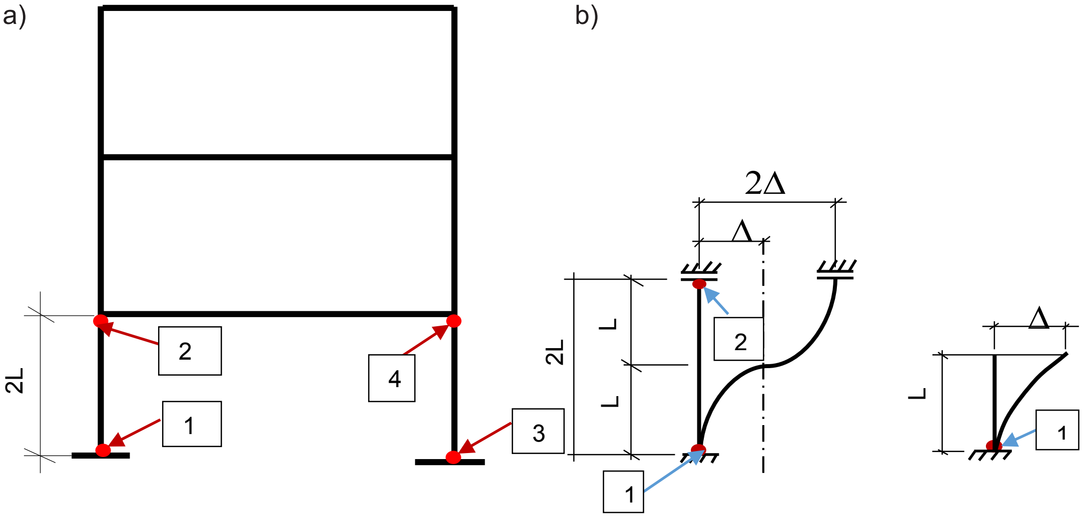

Figure 6. Transition from frame to equivalent cantilever beam:
a) Location of plastic hinges, and b) schematization of equivalent cantilever beam

The desired ductility (plastic properties) of structures are then optimized, to withstand a given earthquake excitation.

Relationship between deformation and displacement under cyclic loading

The level of damage to structures due to seismic influence depends not only on the maximum response in terms of forces or lateral displacement. Inelastic excursions below the maximum lateral displacement capacity of the structure can still cause significant damage (low-cycle-fatigue). This duration-related cumulative damage from multiple cycles of elastic-plastic deformation has to be accounted for during seismic action on structures. For cyclic deformation with different amplitude, it is convenient to use Martin low-cycle-fatigue criteria based on the Coffin-Manson's criteria:

$$\sum_{i=1}^{z}\Delta\,\varepsilon_i^2 \le \varepsilon_B^2 \text{ or } 2\sum_{i=1}^{Z}\Delta\,\varepsilon_i^2 \le \varepsilon_B^2 \qquad (30)$$

where ε_B tensile deformation, z is the number of half cycles, Z is the number of cyclic loading.

If all cycles are the same, then

$$Z\Delta\,\varepsilon_i^2 \le \frac{1}{2}\varepsilon_B^2 \Rightarrow Z^{\frac{1}{2}}\Delta\,\varepsilon_i \le \frac{\varepsilon_B}{\sqrt{2}} \qquad (31)$$

The least or non-damage conditions for a system (structure) under elastoplastic cyclic loading, from seismic excitation can be obtained by relating expressions (30) with (31) as follows

$$\sum_{i=1}^{z}\Delta\,\varepsilon_i^2 \le \left[\sum_{i=1}^{z}\left|\Delta\,\varepsilon_i\right|\right]^2 \le \varepsilon_B^2 \qquad (32)$$

From (32) we obtain the following equilibrium condition of stability:

$$\sum_{i=1}^{z}\left|\Delta\,\varepsilon_i\right| \le \varepsilon_B \qquad (33)$$

Applying the criteria in (33) to the above-mentioned method for equivalent cantilever beams (29) and expression (24), we obtain:

$$\left|\varepsilon_i\right| = \frac{h\,\Delta_i}{l^2}\left(\eta+2\right) \qquad (34)$$

$$\sum_{i=1}^{z}\frac{h\,\Delta_i}{l^2}\left(\eta+2\right) \le \frac{h}{l^2}\left(\eta+2\right)\sqrt{tSED} \le \varepsilon_B \qquad (35)$$

The expression (35) can be adopted as a criteria for seismic resistance (stability), based on an assessment of the input energy under elastoplastic loading of a structure during an earthquake.

It should be noted that the proposed assessment is correct only for the design schematic shown in Figure 6, i.e., for plane frame system. In this case, having performed limit equilibrium analysis the top displacement of the frame is geometrically, linked to displacement of an equivalent cantilever beam. As a consequence of such geometric transformation, equation (35) is applied which does not include the value of $f_{\max}$. However, the distribution of energy between the structural elements may be different. Among others, a certain relationship defining the distribution of input seismic energy among individual structural elements. In this case, $f_{\max}$ will be used during the stress-strain state analysis of load-bearing structural members.

Analysis and discussion of results

Comparative analysis seismic input energy

A non-linear analysis was performed in *Nonlin* for an elastoplastic SDOF system (Figure 1) described by the differential Eq. (9), from seismic excitation. The assessment is carried out for a unit mass system with 0% damping to estimate the real input energy into moderate systems with periods within the range of 0.02 – 2.0s (f = 0.5 – 50 Hz), from 4 earthquakes excitations imposed in the form of accelerograms (Table 1). PGA is peak ground acceleration, PGV is peak ground velocity, SED specific energy density, t_{td} is the total duration and t_{sd} is significant duration.

The maximum yield (ultimate) load was defined as $f_{\max} = PGA$, where *PGA* is peak ground acceleration. The total duration of each excitation is taken as interval between 5 and 95% accumulation of Arias intensity (significant duration) Trifunac and Brady (1975) that characterizes the duration of strong motion.

The predominant period of the ground (T_G) is determined based on the soil type. These values are taken as 0.4, 0.6, 0.8 and 1s for soil type I, II, III and IV respectively (Khashaee *et al*., 2003). Values of PSV, CAV, I_A and SED for specified impacts are determined in the *SeismoSignal and* seismic input energy estimates based on assessments in Eqs. (1), (2), (4), (7) and (21) are also evaluated and the results compared (Figure 7).

The results obtained shows that values of the input energy vary significantly, depending on the proposed method, which is explained by the use of different parameters and assumptions. In some

Table 1
Earthquake records

Earthquake name	Country and date	Component	PGA (m/s²)	PGV (m/s)	SED	t_{td} (s)	t_{sd} (s)
Kobe	Japan, 1995	0°	4.99	0.36	0.164	40,95	9.73
Avej	Iran, 2002	Long	4,37	0.25	0.028	58,86	6
Loma Prieta	1989	270°	2,7	0.37	0.108	40	7,8
Parkfield	1971	40°	2.33	0.11	0.026	26.2	13,8

cases, the obtained values of maximum seismic energy are underestimated compared to the real values from equation (9). Consequently, it can result to underestimation of the desired ductility (plastic properties) which in turn govern the structural resistance, should be based the accurate assessment of the input energy into the structure (or system). It is important to note that the proposed assessment (21) always give seismic input energy value above the real values, thereby excluding any possibility of inadequate ductility during energy-based design.

Determination cyclic deformation in a SDOF multi-storey plane frame

To determine the cyclic deformation in multi-storey plane frame SDOF system (Figure 7), the following parameters and seismic excitations (Table 2) were used

$$h = 0.4\text{m},\ l = 3.5\text{m},\ \eta = 5,\ \varepsilon_B = 0.2,$$

$$\sqrt{\tilde{t}SED} = E_{SED}/f_{\max},\ f_{\max} = \lambda PGA,\ \lambda = 0.25$$

where l is length of equivalent cantilever beam, h is section height of beam, η is bending parameter, ε_B is permissible deformation limit, λ is yield force reduction factor.

The results (Table 3), indicate that for seismic excitations 2-10, the deformation in the system are within acceptable limits. However, for the first excitation, the deformation exceeds the permissible value. This means that to ensure the seismic resistance of the system, it is necessary to make corrections to initial design data.

Conclusions

This work has shown that the value of the seismic input energy into system from seismic excitation differ, significantly, depending on the method used. It is important at the initial design stage not to underestimate the input energy, as it will undermine the provision of desired ductility, which in turn governs the seismic resistance.

The procedure proposed always evaluates the seismic input energy above the real values with reasonable margin of safety, which excludes the possibility of underestimating the desired ductility. This procedure is performed without recourse to dynamic analysis and is a convenient tool for selection of key design parameters at the initial design stage.

Table 2
Characteristics of earthquake records

No.	Earthquake	PGA (m/s^2)	SED (m^2/s)	Duration, t (s)
1	Chi-chi	4.32	2.442	26.49
2	Friuli	3.43	0.025	4.24
3	Kobe	5.00	0.164	9.73
4	Kacaeli	3.51	0.314	10.56
5	Northridge	9.15	0.388	8.53
6	Ano Liosia_K	3.01	0.007	4.41
7	Ano Liosia_S	2.38	0.006	3.86
8	Avej	4.37	0.024	6
9	Kozani	2.04	0.005	6.46
10	Montenegro	2.62	0.020	9.95

Based on the definition of seismic input energy proposed, a relationship is established between deformation and total cyclic displacement, and low cycle fatigue criteria. These set of proposed formulae and methods allows us to assess the behaviour of a structural system from earthquakes.

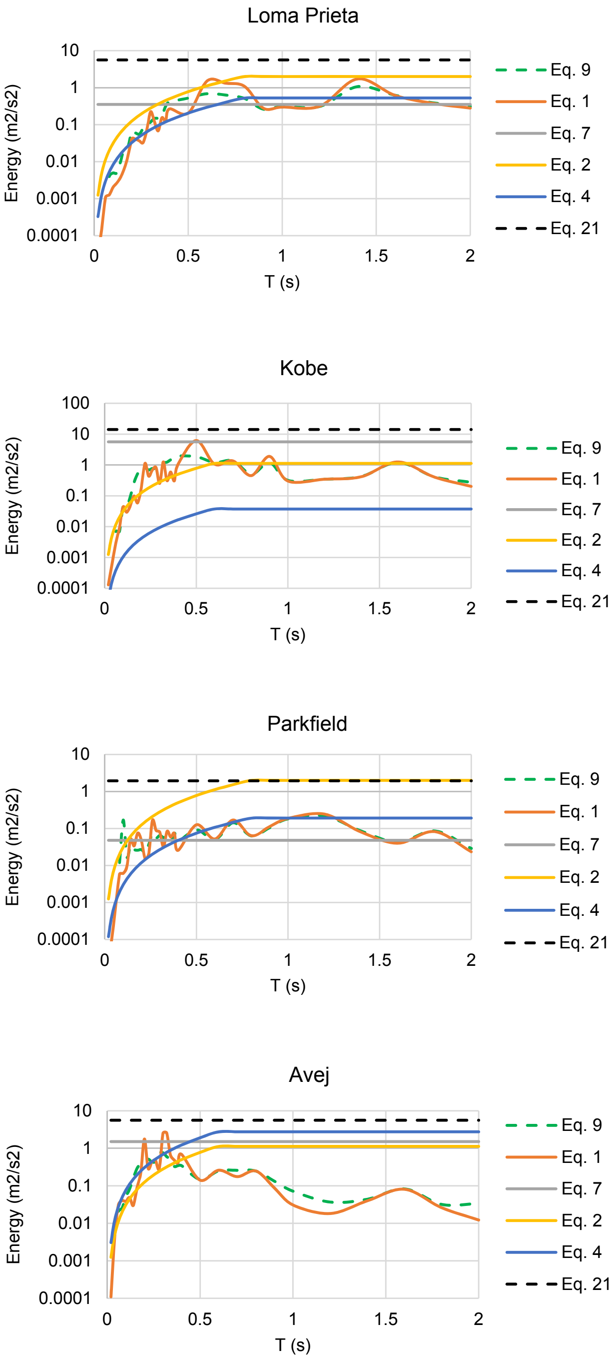

Figure 7. Seismic input energy into various systems from earthquake excitation based on different proposals

Table 3
Cyclic deformation of elastoplastic system with single degree of freedom

No.	Accelerogram	$\sqrt{\tilde{t}SED}$ (м)	$\frac{h}{l^2}(\eta+2)\sqrt{\bar{t}SED}$	ε_B
1	Chi-Chi	8.049	1.839	0.2
2	Friuli	0.326	0.074	
3	Kobe	1.259	0.288	
4	Kocaeli	1.810	0.414	
5	Northridge	1.827	0.417	
6	Ano Liosia_K	0.174	0.040	
7	Ano Liosia_S	0.153	0.035	
8	Avej	0.385	0.088	
9	Kozani	0.179	0.041	
10	Montenegro	0.441	0.101	

Recommendations

This research has shown that wide application of the energy method to the analysis of earthquake resistance of structures requires further development. First, it concerns the development of other (beyond the suggested) a unified approach for assessment seismic input energy and secondly, methods of distribution of seismic energy among elements of the structure (building).

The method and procedure proposed in this research work is recommended at initial stage of design, thus avoiding the consideration of numerous non-functional options of load-bearing structures.

Further development of the topic should be aimed at establishing a unified procedure for estimating seismic input energy and method of distribution of input energy among the various structural elements (building).

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AN INTERACTIVE CONSTRUCTION PROJECT FOR METHOD OF STATEMENT BASED ON BIM TECHNOLOGIES FOR HIGH-SPEED MODULAR BUILDING

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Abstract

The concept and methodology for interactive design of Methods of Statement based on the use of technical and informational models, technological charts, and 3D models of construction facilities is suggested. The article presents the peculiarities and principles for the speed-up assembling (erection, disassembling) of unified modular structures, pre-fabricated block sections, their transportation and rapidly erected modular buildings. The high speed of construction is reached due to the qualitative interactive Method of Statement, logistics of sequence and completeness of information, use of BIM technologies, unconditional use of permanent quality control of works execution at all construction stages with the automatic control of accuracy as to positioning of construction structures and execution of construction and technological operations.

Keywords

Fast assembly, pre-fabricated unified modular structures, rapidly erected modular buildings, the high speed of construction, method of Statement, logistics, BIM technologies, quality control, accuracy control

Introduction

In the modern context of construction operations, there is the burning need for elaboration of a comprehensive assessment methodology and analysis for engineering solutions efficiency, selection of a rational technology for bulk modulus erection in definite construction conditions. It is impossible to speed up the scientific and technical progress in the field of high-speed construction of modular buildings without large-scale implementation of principally new technologies ensuring high labor capacity, efficiency and quality of modular buildings erection. The search for the optimal technology for modular buildings construction is connected with the definition of cumulative parameters and characteristics of the system providing the minimization of stated costs, labor input and work duration, social and economical, ergonomical and other requirements (Adam, 2001; Asaul, et al., 2004; Afanasiev, et al. 2000; Afanasiev and Afanasiev, 1998; Bolotin, et al., 2011; Verstov and Badyin, 2010; Kazakov and Sychev, 2015).

In recent years in the construction practice, we rarely meet a detailed Method of Statement. It is explained for the following reasons: unavailability or respective companies and specialists, qualified designers, construction engineers able to quickly and qualitatively perform the project order; outdated regulatory reference base considering for the project safety, environmental compatibility, efficiency, constructability; non-availability of orders and necessity for the mandatory availability of this document, Method of Statement, for the project construction and handover to the State Commission. Instead of the detailed plan for the Method of Statement, the quarterly schedule for extent of financing is presented. The dynamic technology for the construction and works execution is replaced with the static master plan combined with the site plan of all the engineering and technical communications. The prevalence of the work organization over the technology often leads to negative issues related to the works safety, accidents, injuries, workers death, buildings structures collapse (Matveyev, 2000; Ugorelova, 2000; Anderson and Anderson, 2007; Day, 2011; Fudge and Brown, 2011; Knaack, et al., 2012).

The Method of Statement is an organizational and process document elaborated for project implementation and working documents preparation and defining the construction works processes (technological processes and operations), quality of their performance, time, resources, and safety events (Central Scientific Research Institute of the Organization for Building Mechanization and Technical Aid, 2007a).

A process flow chart is the organizational and process document elaborated for the performance of processes and defining the composition of operations and mechanization means, quality requirements, labor input, resources and safety events (Central Scientific Research Institute of the Organization for Building Mechanization and Technical Aid, 2007b).

Summing up the above, we may say that there are contradictions in the design documents for the Method of statement mandatory for completion at construction of any facility.

Subject, tasks and methods

The main aim of the researches from Saint Petersburg State University of Architecture and Civil Engineering is the developing the first Russian **interactive Method of Statement based on BIM (Building Information Modelling) technologies suggest the concept** which according to the technology designers assessment will allow for anytime obtaining of multidimensional visualization of erection of building structures, complex joints, accuracy of technological equipment structures and units positioning due to the sensors installed in erection elements. Designers and builders in the course of construction and erection works execution will be able to see the way and sequence, use of technical tools (cranes, hoists, winches, etc.) to be applied for erection (assembling, disassembling) of structures or another task. Implementation of interactive technological erection processes will allow for fundamental changing and supplementing the applicable system for construction and technological project preparation. Thereby the reliability, strength, stability, safety of a certain working process may be multiply checked. The result is that we will reduce construction duration, labor capacity, reach the right price and quality ratio for the project, save on new pre-fabricated parts production. Project errors risks decrease significantly, the working documents quality enhances and by extension, the construction works execution quality. The interactive work differs from the common virtual reality as follows: a designer sees the surrounding environment with consideration of additional factors and conditions in which a designed project will be erected. In course of design the information is introduced through the special glasses which may have set visual commands ensuring a step-by-step guidance of technological calculations, options for equipment positioning or right actions of an engineer (Badyin and Sychev, 2015; Kazakov, et al., 2015; Sychev, 2015a; Sychev, 2015b).

The main purpose for creation of the interactive Method of Statement is to realize the tools allowing on the basis of objective (i. e. received with use of measurement devices with a definite accuracy class depending on the control requirements and undergone the state certification through checking laboratories) and actual data for creation of the models of constructed (restorated) facilities and make analysis and conformity assessment of the current status (condition) of real facilities at all construction and restoration stages to the accepted design and construction solutions with successive evaluation of scope and cost of the executed works (Figure 1). Besides the system of the interactive Method of Statement is to be able to introduce necessary changes into facilities construction (restoration) schedules on the basis of obtained data which characterize the conformity of the current status of facilities construction (restoration) to the requirements of planning and controlling authorities. On the interactive Method of Statement basis, it is possible to build up the system for support and decision taking for the construction industry (its sections) control and management authorities. The most important function of the interactive Method of Statement is the search of most rational options for control and management with due consideration of various factors impact.

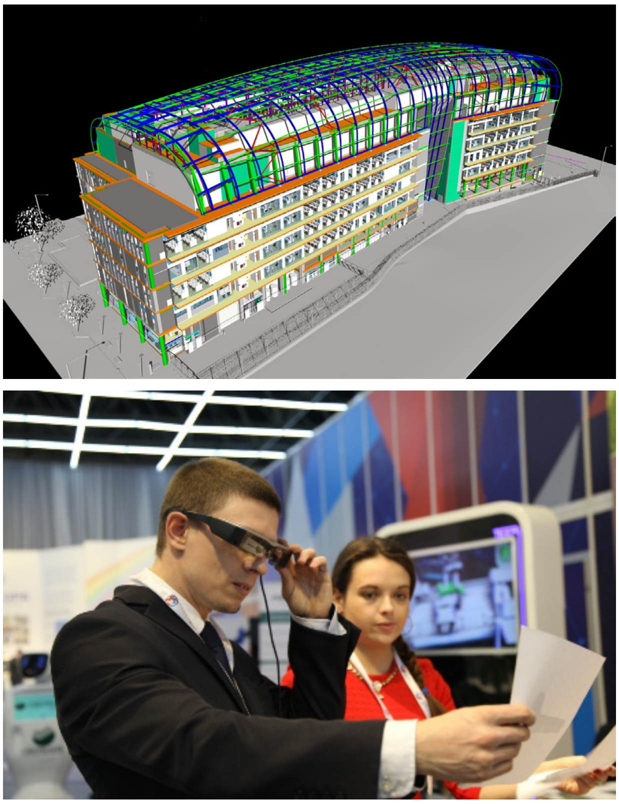

Figure 1. Interactive model of the Method of Statement for high-speed buildings erection with modular attics (on the left) and construction virtual reality means (on the right) based on BIM technologies

The main method, which is used in the authors' research is the combination of BIM and real-world example of the construction progress, which is integrated closely enough with structures stocks, machines fleet, regulatory requirements, technical regulations considering construction quality control, safety, reliability, efficiency (Figure 2).

Results

On the face the glasses do not differ from common ones however they show the additional information about many characteristics and technical and economical values of processes: movement speed of cranes, machines, mechanisms, transport; safe operational distance; productive and labor capacities; In the perception of the authors the technology of interactive Method of Statement will allow for receiving of 3D visualization of such processes as structures erection, assembling of complex joints and units of technological equipment considering works execution safety and erection accuracy with use the installed piezometric senses, GPS or GLONASS senses. Materially all norms of set of rules (SP), SNiP, ENiR, VNIR, TER, MRT, etc. are included in the PC memory with glasses intake unit. There is no need for a paper drawing in many copies.

In AutoCAD in the coordinate imaging system it is possible to design the electronic version of all plants, erection elements tying-in to a building grid for spatial orientation of erection of structures with senses, elements cut and paste and object editing; to inspect various variants and versions many times prior to print out. Several floating viewports for complex object may be created. Following the comparative analysis and comparison, the optimal variant is to be selected as the final solution of a certain engineering task.

BIM Method of Statement presents the possibility of operative obtaining of required information often without any additional queries to a designer and line management. The advantages of the technology for the interactive Method of Statement BIM are evident for the model allows for monitoring the project from inside with all its interrelations and details of space and planning and engineering and technological solutions, applied materials and equipment.

Construction companies in the course of the developer's project implementation face the necessity for the control of completeness and quality of construction and erection works execution. It is possible to timely obtain actual information about construction progress, constantly control execution of technical plans for construction from various sources: reports, communication means, construction sites. However, there is a more efficient, simple and fast way of obtaining the information for taking decisions — the construction progress control system. It allows obtaining evaluation summaries for all the constructed facilities in real time and if required perform the operative analysis of critical situations by a foreman, a site supervisor, chief engineer.

Thus, the interactive system for control of the works execution, as the main research result, is the uniform closed electronic space created by integration of information technologies used by all the specialists participating in implementation of a facility — from survey and design to construction. The implementation of such system for the works execution is to be considered as an innovation approach aimed at getting new competitive advantages by a construction company and receiving true economic feedback from the funds invested into the project. The informational system of the interactive Method of Statement being correctly adjusted is aimed at constant monitoring of ongoing processes in a monitored facility as regards the set program of its development, helps to reveal causes of arising deviations, non-use of reserves and possibilities of enhancing of construction efficiency, helps to elaborate variants of optimal solutions for elimination of an occurred unfavorable situation in the form of inaccurate erection of structures, violation of requirements of the Method of Statement, concealment of defect (Figure 2).

Accordingly, the objective control service of construction stages by means of the interactive Method of Statement lies in the formation of the generations of spatial data on a constructed facility and is as follows (Figure 3):

- Service of gathering information on the basis of satellite data, aerial photography and surface laser scanning as the complex of events aimed at the formation of the generations of spatial data, submission of spatial data for control function implementation including the stage of design and survey works.
- Service of data processing including the innovative technologies for digital processing of

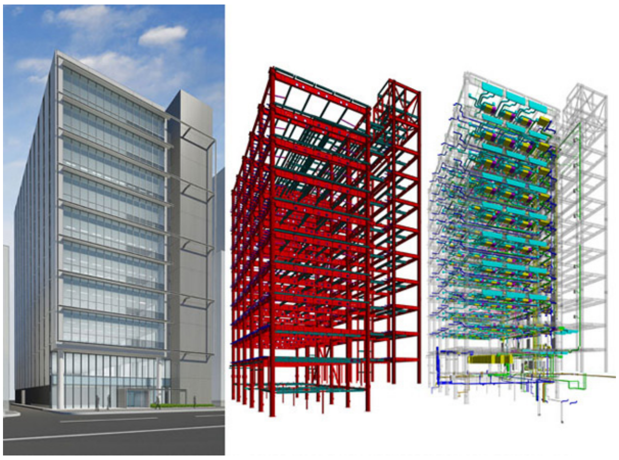

Figure 2. The example of building 3D model of a rapidly erected modular building as the basis for creation of the 5D interactive Method of Statement based on BIM technologies

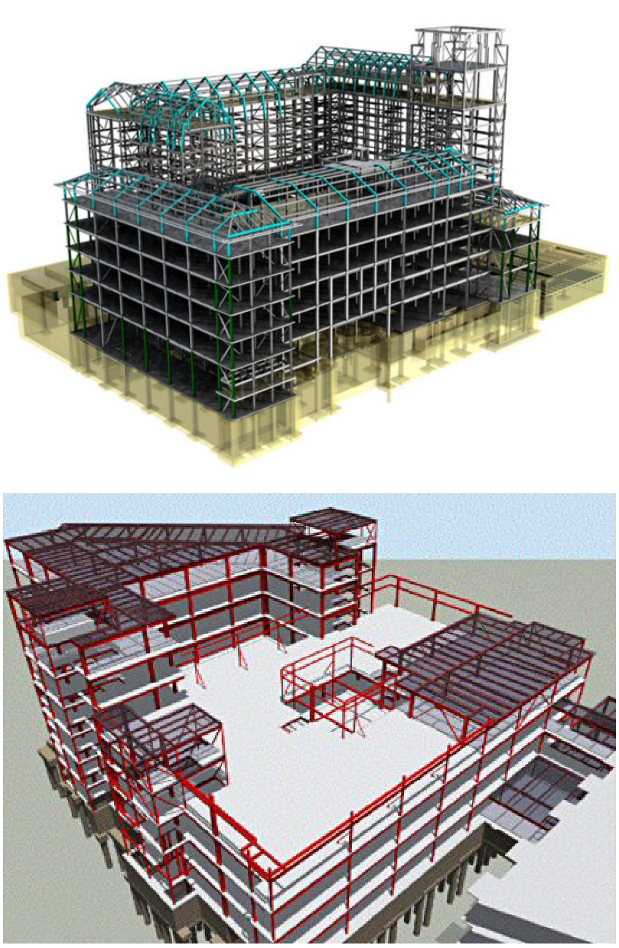

Figure 3. An example of building 3D model of a rapidly erected modular building with attics as the basis for creation of the 5D interactive Method of Statement based on BIM technologies

spatial data, assessment of construction stages and infrastructure status as well as performance of international norms and requirements of GOST, SP, SNiP.

- Service of analysis, evaluation and visualization of objective information representing the system of events for comparing of the data available on current construction progress of facilities to the design and engineering documents as consistent with construction stages, GOST requirements and regulatory and technical documents including design and engineering ones and keeping the data base up to date.

The interactive control procedure contains several stages. Control measurement is executed one time in a reporting period (e.g. upon closure of a working day). The measurement results are incorporated into respective reporting documents, estimates, etc. as per a regular procedure by an authorized person (controller, foreman, etc.). The survey of a construction facility is taken form fixed locations, viewing angles, etc. with tools by the same authorized person or fixed cameras. The reports are incorporated in databases for data upload into GIS according to BISDM model. The key procedure is the comparison of real construction parameters with design documents. The main sources for data comparison are as follows:

- Reporting documents for the reporting period (incorporated as data bases or respective clauses).
- Field survey results.
- Facility GIS–BISDM-model received from CAD.
- Actual building condition GIS-model (BISDM).

The geoinformation model based on ArcGIS is an architectural solution for the objective control system for construction projects. Modern construction objective control means operate with 4D-models of constructed facilities. 4D unites the facility 3D-model with the respective works of activity progress chart of construction works and includes the 4 parameters: three spatial coordinates and time. Such model allows for visual monitoring of all planning errors by modeling the construction process in time. It is worth noticing that the basis for any objective control system is the geoinformation system (GIS) which is the virtual representation of a construction site (or sites) where facilities are interrelated in geographic space. GIS allows users to get the access to an information model, construction works schedule and other information as to the selected facility and allows management of all levels to assess overall construction progress on all sites. It is possible to say that objective control means represent a special GIS realizing GIS potential and technological solutions for collection, processing and creation of required data on a construction facility.

For recent 30 years, the main methods for forming and management of the construction environment and in adjacent industries have turned out to be unstable. Currently the interested parties most often use in construction projects such technologies as building information model **(BIM)** among other traditional computer-aided design systems **(CAD)** in order to create and store the data on buildings. Besides, **BISDM** (the information model of a building internal space, data model used in GIS software and allowing for efficient geodata exchange and interaction with other platforms (Figure 4, 5). The task for heads of construction companies is query, analysis and submission of this information for all buildings within a district or even more geographic region. Thereby in many cases the construction data is contained in electronic tables and paper or electronic floor-plans without an actually organized data management system.

On account of import and aggregation in GIS of geometric and text data from several files BIM and/or CAD, all the potential of BIM Method of Statement may be used and extended by way of its integration with related spatial data on the neighbourhood area, district, region (Figure 6).

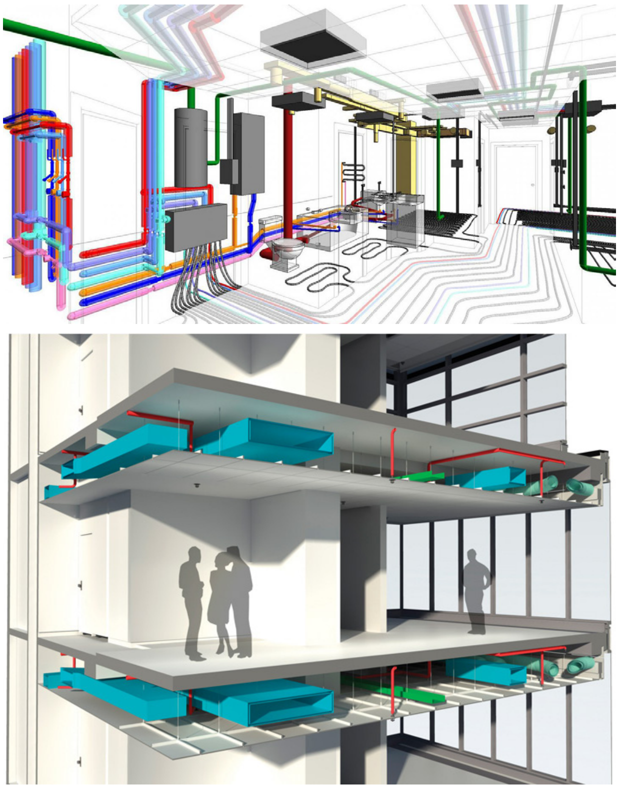

Figure 4. Building of the 4D of a rapidly erected modular building with specification of installed utilities as the basis for the creation of 5D interactive Method of Statement based on BIM technologies.

A significant role in construction project management is played by Integrated Workplace Management System (IWMS). A comprehensive part of the entire construction project life cycle management may be done with use of the program **IBM TRIRIGA**. TRIRIGA functionality allows for solving of the whole set of tasks as regards construction, monitoring and maintenance. The program may be supplied modularly depending on the customer's requirements.

Conclusions

The main results are given in the general conclusions of the article. Currently the authors make elaborations in field of compatibility of calculated, regulatory and BIM models of a building. In future, it will be possible to introduce corrections to the BIM model based on the results of calculation in the mode of conversion of calculated program complexes files, which will help to avoid the non-compliance of a building calculated model and accepted structural and technological solutions and will make the expertise of a constructed facility and the construction and erection works execution more efficient.

The main conclusions are:

1. This work suggests a methodology (methods, algorithm, software) for high-end system rapidly erected modular buildings, the dependence of the assembly parameters on the technological characteristics of prefabricated modules, comprehensive mechanization facilities and automation of the erecting equipment was defined (operation time and work labour input decreased by 40%, the accuracy of mounting joints increased by 50%).
2. An interactive project of execution of work based on technical and information models, flow diagram and miniatures of construction projects in 5D system of unified modular constructions was developed. New interactive Method of Statement takes into account the dynamic changes of the construction. It is the operative document, based on the vast database of the experimental data on materials, machines, automatic mechanisms, processes and methods of construction.
3. This work suggests the system of complex-virtual support for visual tracking and the choice of the work production optimum alternative and the construction planning design, which eliminates the need to print a large volume of paper documents. The visual design based on the interactive Method of Statement increases the quality of the work

Figure 5. Building of the 4D model of the interactive Method of Statement for the modular building erection works as the basis for the creation of the 5D model based on BIM technologies

Figure 6. BIM data imported into GIS combined in the common 5D model (coordinates, time, movement) of construction and erection works execution with the possibility of movement across a facility and imbedded into «visual environment»

production plan and the construction method statement by 50-55%: during the assembling saves up to 15% of the work and materials cost; saves up to 20% of the time during the assembling modulus; saves the expense of accuracy of calculations up to 10%; saves up to 30% of payroll; saves up to 20% of the equipment and materials value; saves up to 30% on the time and cost of designing.

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CONTROL OVER DISTRIBUTION OF CONSTRUCTION LOADS ON FOUNDATIONS OF TOWER BUILDINGS

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Abstract

The article describes the tasks and traditional approach to organization of full-scale instrumental observations over vertical deformations of engineering tower structures. Issues related to interpretation and use of the results of repeated geodetic observations during the study of tower structure foundation deformations are considered. The article presents an algorithm for processing of the results of repeated leveling of deformation control benchmarks set along the foundation perimeter, which allows calculating mutual displacement of settlement points due to local deformations of foundations, accompanying gradual settlement of foundation base groups. A possibility of identifying a direction of total foundation inclination is outlined for the purpose of effective management decisions related to adjustment of construction process with regard to redistribution of loads along the perimeter of tower structure foundation with the aim to eliminate its inclination.

Keywords

Tower structures, settlement, deformations of foundations, repeated geodetic observations, foundation inclination, redistribution of loads on foundation, elimination of foundation inclination

Introduction

Modern engineering tower structures, behavior of which depends on strict adherence to design solutions during construction and their stability during maintenance, include reactor buildings and cooling towers of nuclear power plants, blast furnaces, elevators, television towers, and other high-rise structures.

High-rise tower structures are characterized by load concentration reaching tens of thousands of tons and more (Mikhelev et al., 1977, Bolshakov et al., 1980) on foundations of small size (more often, base slabs). Heavy concentrated loads on foundations and their beds cause rapid and considerable settlement of high-rise structures under construction.

A distinctive feature of high-rise tower structures is their sensitivity to relatively inconsistent foundation inclinations due to non-uniform deformations (compaction) of foundation subgrades. Non-uniform deformations of subgrades occur often because of uneven construction loads on the foundation, even upon homogeneous structures and physical and mechanical properties (compressibility).

Subject, tasks and methods

Construction technology for tower structures provides for support of construction works with geodetic surveying to observe possible deformations of erected structures. Suffice to say that every single construction of tower structures is completed with repeated high-precision geodetic surveying revealing presence or absence of foundation settlements, i.e. passive control of foundation settlements and such generated deformations as inclinations is performed.

The practice of geodetic surveying of deformations of tower engineering structures (Bolshakov et al., 1980; Bright et al., 1959; Ganshin et al., 1981; Clough et al., 1979; Mikhelev et al., 1977; Volkov, 2015; Costachel, 1967; Mishra, 2011; Rincon, 2013) points out the necessity to monitor distribution of construction loads, transmitted from a part of the erected tower structure to the foundation and soils, with the help of repeated geodetic observations providing reliable designed condition of structures both during its construction and maintenance.

There is no method of distribution of construction loads during construction of tower engineering structures using results of repeated high-precision and accurate geodetic observations which include repeated leveling of deformation control benchmarks along the perimeter of foundation slabs of erected high-rise structures. Passive control of settlements of such deformation control benchmarks allows only calculation of inclinations in separate directions connecting two deformation control benchmarks, but does not allow establishment of total inclination of the foundation slab and its azimuth, which, in its turn, eliminates ability to control and modify construction loads, leading to inclinations of erected structures.

To solve these problems, a special technique of processing of the results of repeated leveling of deformation control benchmarks was developed; this technique allows control and distribution of loads across foundations of tower structures under construction with the help of identified total inclinations of foundations, occurring as a result of total gradual settlements, followed by development of an algorithm for their elimination.

Results and discussions

The essence of the proposed method is as follows. Non-uniform deformations of the structure foundations generate their inclinations which are characterized by indicators well-known in the engineering and geodetic practice, such as inclinations in the direction of longitudinal i_x and transverse i_y axes of the structure (Bolshakov et al, 1980; Kosterin, 1990; A. Filiatrault et al., 2013; Paz, 2012). In order to adjust the construction flowsheet, the proposed method allows for establishment of the maximum increasing amount of inclination of the structural foundation i_{max} and its direction (azimuth). To this end, deformation control benchmarks are marked along the perimeter of the foundation of the erected tower structure (Figure 1), which after a period of time T are repeatedly leveled (leveling of Class I and II, 1982; Zharnikov et al., 1990). The first and subsequent cycles of repeated geodetic observations include laying of leveling lines from the reference benchmark to each deformation control benchmark $j=\overline{1,m}$. According to the results of the first cycle of leveling, exceedances between deformation control benchmarks and their levels H_1, H_2, …, H_m are determined.

By taking deformation control benchmarks *1, 2, …, m* by turn as the origin of coordinates, the levels of remaining deformation control benchmarks are calculated on the basis of exceedances in two compared cycles. Comparing the levels of deformation control benchmarks received during two cycles, we receive the first row of discrepancies δ_{kj}. Similarly, taking the *2nd, 3rd, ..., m-th* deformation control benchmark as the origin of coordinates, we get *m* rows of discrepancies δ_{kj} ($k=\overline{1,m}$ and $j=\overline{1,m}$ are the numbers of deformation control benchmarks, respectively, for which discrepancies between levels and values taken as the coordinates origin are calculated).

Thus, these rows of discrepancies are tabulated (Table 1), revealing a quadratic symmetric matrix A_m with diagonal elements $\delta_{kj}=0$ symmetrically equal in absolute magnitude but opposite in sign to non-diagonal elements $\delta_{kj}=-\delta_{jk}$.

$\delta_{av.j}$ value is the value of average displacement of j^{th} deformation control benchmark in relation to all deformation control benchmarks, occurred during a period of time T between two cycles of repeated leveling.

Estimation of destabilization or invariance of the level of deformation control benchmarks during a period of time T is carried out on the basis of analysis of values $S_{av}=\frac{[\delta_{kj}]}{m-1}$. Benchmarks falling within the inequality $|S_{av}| \le t_\beta \mu \sqrt{\pi S_{av.j}}$ (where μ is the mean square error of the unit weight, $\pi S_{av.j}$ is a reverse weight of value $S_{av.j}$, t_β is a coefficient of conversion from mean square errors to limit errors) refer to deformation control benchmarks that have preserved their high-rise level (Volkov et al, 2015; Mikhelev et al., 1977). Otherwise, the deformation control benchmark belongs to the category of unstable values, i.e. benchmarks with considerable settlement.

Differences of significant average displacements $\delta_{j+1}-\delta_j$, $\delta_{j+2}-\delta_j$, …, $\delta_{j+m}-\delta_j$ reveal reciprocal (local) displacement of deformation control benchmarks *j* and *j + 1*, *j* and *j + 2*, ..., *j* and *j + m* during a period of time *T*.

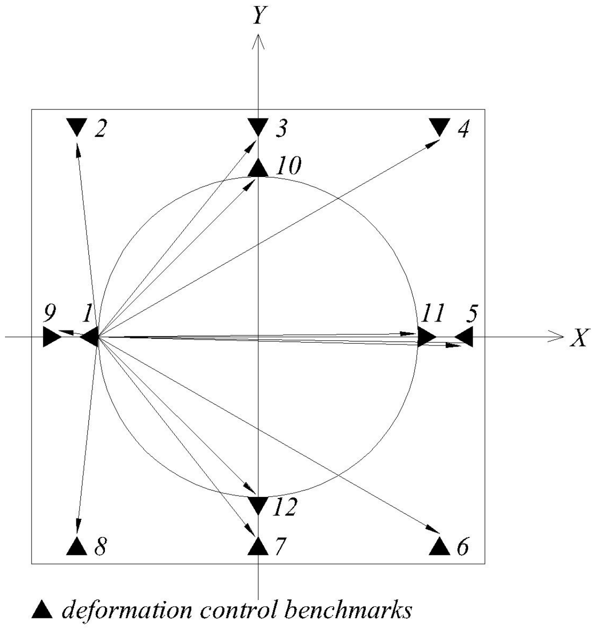

Figure 1. Layout of deformation control benchmarks (through example of a foundation slab of a reactor building of a nuclear power plant)

Table 1
Values of average displacement of deformation control benchmarks

j / k	Number of an original deformation control benchmark					
	1	2	3	4	…	m
1	0	δ_{12}	δ_{13}	δ_{14}	…	δ_{1m}
2	δ_{21}	0	δ_{23}	δ_{24}	…	δ_{2m}
3	δ_{31}	δ_{32}	0	δ_{34}	…	δ_{3m}
4	δ_{41}	δ_{42}	δ_{43}	0	…	δ_{4m}
…	…	…	…	…	…	…
m	δ_{m1}	δ_{m2}	δ_{m3}	δ_{m4}	…	0
$[\delta_{kj}]$	$[\delta_{k1}]$	$[\delta_{k2}]$	$[\delta_{k3}]$	$[\delta_{k4}]$	…	$[\delta_{km}]$
$\frac{[\delta_{kj}]}{m-1}$	$\frac{[\delta_{k1}]}{m-1}$	$\frac{[\delta_{k2}]}{m-1}$	$\frac{[\delta_{k3}]}{m-1}$	$\frac{[\delta_{k4}]}{m-1}$	…	$\frac{[\delta_{km}]}{m-1}$

Taking one of the main axes of the tower structure (foundation), passing through one of the invariable deformation control benchmarks (reference), as an “original” point, we determine direction azimuth *A*, passing through the reference and other benchmarks (according to our example (Fig. 1) — $A_{1\text{-}2}$, $A_{1\text{-}3}$, $A_{1\text{-}4}$, …, $A_{1\text{-}12}$). Separate inclinations $i_{1\text{-}2}$, $i_{1\text{-}3}$, $i_{1\text{-}4}$, …, $i_{1\text{-}12}$ are defined according to selected directions 1-2, 1-3, 1-4, ..., 1-12:

$$i_{1-2} = \frac{\delta_1 - \delta_2}{T \cdot S_{1-2}} \rho'',\ i_{1-3} = \frac{\delta_1 - \delta_3}{T \cdot S_{1-3}} \rho'',\ ...,$$

$$i_{1-12} = \frac{\delta_1 - \delta_{12}}{T \cdot S_{1-12}} \rho'', \tag{1}$$

where *S* is the distance between the “original” and j^{th} deformation control benchmarks, $\rho'' = 206265''$.

Inclinations of the foundation (in our case, of the foundation slab) along the selected directions are represented with equations forming the following system:

$$\begin{aligned} i_{1-2} &= i_x \operatorname{Cos} A_{1-2} - i_y \operatorname{Sin} A_{1-2} \\ &\cdots\cdots\cdots\cdots\cdots \\ i_{1-12} &= i_x \operatorname{Cos} A_{1-12} - i_y \operatorname{Sin} A_{1-12}, \end{aligned} \tag{2}$$

where i_x and i_y are separate inclinations along the selected directions, defined according to the system of equations (2) with the least-square method.

The value of the total inclination in a linear measure is calculated with the following formula (Volkov, Severgin, 1989):

$$I = \sqrt{i_x^2 + i_y^2}. \tag{3}$$

The azimuth (grid azimuth) specifying the direction of the total inclination is calculated according to the formula (Volkov, Severgin, 1989):

$$\text{arctg}\, A_{tot} = \frac{i_y}{i_x}. \tag{4}$$

The further loading of the slab along the line with azimuth A_{tot} ± *180º* leads to decrease of inclination with regard to the foundation and the whole tower construction as a consequence.

Conclusions

The proposed method makes it possible to draw load diagrams for foundations of tower structures (reactor buildings of nuclear power plants, elevators, blast furnaces, etc.) according to repeated geodetic observations, taking into account uneven deformations of foundation soils during construction.

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