Design of the bracket’s structures and their bracing for industrial climbers' service of high-rise buildings with facades of solid glazing

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Abstract. The article presents one of the possible options for solving an urgent engineering problem of the development of special devices and their arrangement in high-rise buildings with continuous facade systems for the possibility of their service. The authors have developed a bracket design in two modifications made of metal plates, which is fastened to the end of a monolithic reinforced concrete slab at the level and along the perimeter of the eaves of the building with chemical anchors of the Hilti HVU series. The nature of the change in the stress-strain state in the plates, main pipes, and in anchor devices of the developed bracket construction was studied by calculation using the usual engineering method, as well as in the generated model in the SOFiSTiK computational and graphic complex. The results of short-term load testing of completed samples of the developed model before serial production are presented. The work of the elements of the developed structures of the brackets under the conditions of the action of an aggressive environment has been analyzed.

1. Introduction

During the construction of high-rise buildings in recent decades, the creation of facades with maximum usage of translucent constructions, including the entire contour, has become widespread in different countries of the world. Examples are the famous buildings: Commerzbank in Frankfurt am Main (Germany, 1997), City Hall in London (GB, 2002), Manitoba Hydro Place in Winnipeg (Canada, 2009).

The usage of the translucent structures allows to diversify the building view and their shapes, which create the modern architectural style and its attractiveness – for example, the One Angel Square building, built in 2013 in Manchester (GB), has a peculiar configuration with a solid glass façade [1]. The construction of buildings with solid translucent facades has been developed in Ukraine too. The reason for the popularity of construction of buildings from translucent constructions is their practicality, reliability, durability, and, important for architects and designers, in a wide variety of types and forms. The translucent façade systems afford not only to insulate and decorate the façade effectively, but also give the building a stylish modern look. At the same time the cost of constructing the facade is considerably lower than for general construction works on its construction in the "standard" concrete form.

Alongside with the listed advantages, the facades of buildings made of solid translucent structures have a number of difficulties in their service, for example, when cleaning the plane of solid glazing from pollution. The solution of this problem by using temporary attachments with the formation of counterweights on the roof or on the upper operating sites of the building creates difficulties associated with the frequency of their arrangement and the cumbersome nature of the equipment used, including the often lack of access to these sites caused by the peculiarities of their operation.

The creation of special devices and technologies for their anchoring to the already existing facade systems in the constructed buildings (see figure 1) has become an urgent engineering task, the solution of which has the great practical importance.
2. The literature review
Engineering solutions for the formation of structures that provide the possibility of servicing facade systems by fixing industrial climbers to main pipes with brackets are based on calculations for the first and second groups of limiting condition, in accordance with the regulatory documents in force on the territory of Ukraine [2,3], and also European standards [4].

Many examples of metallic construction calculation are described in some detail in the designer’s guide [5].

The joint operation of metal expanding anchors in a concrete environment is described in [6].

The calculation of plates with variable rigidity under the load in the transverse direction is described in the works [7,8], in which are also considered the plates pinched on one side. For such plates, the boundary conditions are used: the deflection and the angle of rotation at the pinched point are equal to zero, which leads to some simplification when writing the basic differential equation of bending of an orthotropic plate of variable rigidity [7].

Analysis of the stress-strain state of plates of variable stiffness, plates with holes, and other analytical methods becomes so time-consuming that in many cases it is not possible to obtain the result in analytical form [8]. The finite element method (FEM) is intended for such complex problems of plate calculation. On its basis, it is possible to solve practical problems of any complexity, including plate systems. In this case, there can be holes in the plates, on a part of the surface of the plate they can rest on an elastic foundation or have a nonlinear nature of deformation, caused by both changes in geometry and taking into account the inelastic properties of materials. Thus, the finite element method allows you to reflect the actual work of the constructions.

Calculation of plates by the finite element method (i.e. determination of the stress-strain state, in particular the calculation of the plate’s deflections), same as by the finite difference method consists in determining the deflections of the finite number of plate’s points - the nods of the discretization grid’s, with the help of which the plate is divided into many smaller plates - finite elements.

3. The aim of the current work is creation of the design of brackets with main pipes to ensure the service of facades from translucent systems in high-rise buildings by industrial climbers; ensuring the reliability of fastening brackets in a concrete slab at the level of the cornice on the perimeter of the building; determination of the stress-strain state in the steel elements of the developed bracket under...
the transverse bend, shear forces and work to tear off the anchoring devices for attaching the brackets to the monolithic floor slab.

4. The materials and the methods
Metal plates and pipes, anchoring devices and a monolithic reinforced concrete slab were used. Determination of stresses and strains in steel elements and concrete of a monolithic reinforced concrete floor slab was carried out by generally accepted methods in accordance with the current regulatory documents [2,3] and using the SOFiSTiK calculation and graphic complex [9].

5. The statement of the main obtained results
The construction of the holding bracket is designed to allow industrial climbers to move in areas or around the entire perimeter of the building along metal pipes at the level of the cornice in order to service the surface of the facade made of solid glass of stained glass type.

The location of the brackets is provided at the same distance along the end of the monolithic reinforced concrete tube. The main parameters of the used metal plates of the bracket were determined initially based on the thickness of the monolithic reinforced concrete slab, as well as by calculation in accordance with the current regulatory documents [2,3].

Figure 2. Construction of the designed bracket according to the assigned engineering task.

As the background information, the following was taken: the size of the plate should not exceed the thickness of the monolithic floor slab; the design load for one tube span is 0.2 kN; fastening of the pipe span with beading in the lugs of the plates is hinged.

The calculated span between the fixed brackets was determined by a calculation that takes into account the dynamic component of the vertical and horizontal load, the force of breaking the anchors from the concrete slab and the degree of possible metal corrosion during long-term operation under conditions of variable exposure to moisture and freezing and thawing.

Initially, the calculation determined the cross-section of the main tube which was broken along the edges with an estimated length of 1.0 m, the installation of which was provided using two intersecting plates fastened by mounting bolted joints (figure 2).
The maximum bending moment perceived by the tube cross-section was determined by the following formula

$$M_{\text{max}} = \frac{P \cdot n_{\text{din}} \cdot f_{\text{cor}} \cdot L_p}{2} = 50$$

where:
- $P$ – given load;
- $L_p$ – the calculated length;
- $n_{\text{din}}$ – dynamic coefficient;
- $f_{\text{cor}}$ – the time-dependent function of corrosive wear;

The required moment of resistance

$$W_p = \frac{M_{\text{max}}}{R_{\text{cr}}} = 12.5sm^3$$

what determined the section of the main pipe on the calculated span Ø83x4 mm.

With the maximum deflection up to 1.1mm, according to the formula

$$f = \frac{5 \cdot PL^3}{384 \cdot EI}$$

The maximum bending moment at the base of the support plate of the bracket was calculated by the formula:

$$M_{\text{opr}} = P \cdot n_{\text{din}} \cdot B_p$$

The breakout force of the anchor from the reinforce concrete slab was calculated by formula:

$$N_{\text{otr}} = \frac{P \cdot n_{\text{din}} \cdot B_p}{b_{\text{kr}}}$$

where:
- $B_p$ – the distance from the axis of the main tube to the bracket’s side;
- $b_{\text{kr}}$ – the minimal indent between the brackets, which are forging the bending moment which supports the anchor from the toppling back.

The selection of the diameter and length of the bracket was carried out according to the condition

$$P_{\text{cr}} > N_{\text{otr}}$$
where:

\[ P_{ecr} = A_{hoe} \cdot R_{bt} = 2\pi r \cdot L_{use} \cdot R_{bt} \]  

(6)

The salvaged elements obtained by the above formulas were compared with the results of the calculation in the software SOFiSTiK [9], the main results of which are given below in the figure 4.

Figure 4. Stresses and strains in the anchor’s elements.

Calculation of retaining vertical plates for the load from shear in the horizontal direction, taking into account the dynamic effect, is possible using the theory of calculation of plates with variable rigidity [7], and also via the calculation and graphical SOFiSTiK [9].

The main differential equation of the bend of the orthotropic plate with a variable rigidity is:

\[
\begin{align*}
&\frac{\partial^4 \omega}{\partial x^4} + 2 \frac{\partial^2 D_1}{\partial x^2} \cdot \frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 D_1}{\partial x^2} \cdot \frac{\partial^2 \omega}{\partial y^2} + \frac{\partial^2 D_2}{\partial y^2} \cdot \frac{\partial^2 \omega}{\partial y^2} + 2 \frac{\partial D_3}{\partial x} \cdot \frac{\partial \omega}{\partial x} \cdot \frac{\partial \omega}{\partial y} + 2 \frac{\partial D_3}{\partial y} \cdot \frac{\partial \omega}{\partial y} \cdot \frac{\partial \omega}{\partial x} + \\
&+2D_2 \cdot \frac{\partial^3 \omega}{\partial x^2 \partial y} + 2 \frac{\partial^2 D_1}{\partial y^2} \cdot \frac{\partial^2 \omega}{\partial x^2} + \nu_2 \frac{\partial D_1}{\partial x} \cdot \frac{\partial^2 \omega}{\partial x^2} + \nu_1 \frac{\partial D_1}{\partial y} \cdot \frac{\partial^2 \omega}{\partial y^2} + 4 \frac{\partial^2 D_1}{\partial x \partial y} \cdot \frac{\partial^2 \omega}{\partial x \partial y} = q,
\end{align*}
\]

(7)

where: 
- \( D_1, D_2 \) - the bend rigidity of the plates in the main; 
- \( D_3 = D_1 \nu_2 + 2D_t \) - the main plate’s rigidity; 
- \( D_t \) - torsional rigidity; 
- \( \nu_1, \nu_2 \) - Poisson’s coefficients of the plate in the main directions; 
- \( q = q \left( \frac{\partial m_x}{\partial x} + \frac{\partial m_y}{\partial y} \right) \).

The analytical solution is reduced to integrating the equation (7) subject to boundary and contact conditions which is well described in the work [7]. This approach is very complex and time-consuming for the engineering task to be performed, and the plates were calculated using a calculation and graphic complex [9], based on the finite elements method. The main calculation’s result is given below.
In order to check the reliability of the selected bracket’s elements and anchors of its bracing to the monolithic reinforced concrete slab and the possibility of further serial development, full-scale tests were performed using a load (figure 6) and via a special equipment (figure 7).

**Figure 5.** Stresses and strains in the anchor’s elements.

**Figure 6.** Testing under the load the fixing link consisting of the two prackets and the pipe.
The final completion of the implemented design development and calculations is the installation of the anchors on the level of the high-rising’s eaves and their use by industrial climbers for the service of the solid glazing facades (figure 8).

6. Conclusion
Designed construction of the bracket with the main pipes and the anchors allows solving the important problem of servicing the facades of high-rise buildings with solid stained-glass glazed.

The reliability of the structure is determined by comparing the calculations performed according to the engineering methodology and using the design and graphical software SOFiSTiK [9], as well as by the carried out full-scale bending and pull-off tests.
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