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RESEARCH ON THE RESISTANCE OF VENTILATED RAINSCREEN FACADES TO DYNAMIC AND VIBRATIONAL LOADS

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Abstract. The study aims to determine the stability of KMD VF ventilated facades, featuring RONSON 250×65×22 Busum facade tiles, when subjected to vibrational and dynamic influences. A key objective is to assess their applicability in seismically active regions of Ukraine. To achieve this, both computational analyses of the stress-strain state of the facade system elements and experimental laboratory tests on a fragment of the system were conducted.

The research methodology involved a comprehensive literature review and analysis of existing technical documentation. An experimental procedure was developed for testing on a vibration stand, utilizing a Vibran-2.0 vibro-analyzer and a universal strain gauge station. A facade system fragment measuring 1000×900 mm was subjected to controlled vibrational loads. Concurrently, a numerical model of the fragment was developed and analyzed using the Lira-SAPR software. The computational results were then rigorously compared with the experimental data, confirming the adequacy of the calculation scheme with an error not exceeding 7%.

Furthermore, a detailed calculation of the facade system's response to seismic loads was performed for a hypothetical 36-meter high-rise building situated in a 9-point seismic zone, in accordance with DBN B.1.1-12:2014. The spectral method was employed, and the computational model utilized volumetric finite elements for the building and clinker, shell elements for brackets and purlins, and special finite elements for modeling connections between clinker-purlins, purlins-brackets, and brackets-building.

The experimental tests demonstrated the facade system's resilience and integrity. No individual tiles detached, and the connection nodes remained reliable, even under load levels corresponding to approximately 60% of a 9-point seismic event. The seismic load calculations further corroborated these findings, indicating that the overall bearing capacity utilization of the system did not exceed 65%, thereby maintaining a substantial 35% safety margin. Crucially, the protection against the fall of individual tiles was ensured with a significant 57% margin.

Based on the comprehensive results obtained from both experimental and computational investigations, it is concluded that the use of KMD VF ventilated facades, adorned with RONSON 250×65×22 Busum facade tiles, is feasible and recommended for construction projects located in seismically hazardous regions of Ukraine.

Keywords: ventilated facades, seismic resistance, dynamic influences, vibrational influences, facade tiles, experimental testing, stress-strain state.

Introduction. Ventilated facade systems (VFS) are an integral part of the modern construction industry, playing a key role in ensuring the energy efficiency, aesthetic appeal, and durability of buildings. These multi-layered structures include a load-bearing frame, an insulation layer, and an external cladding layer with a ventilated air gap. They are widely used in both new construction and in the reconstruction and major renovation of existing structures. Their purpose is to improve the thermal performance of external enclosures and effectively protect buildings from aggressive atmospheric influences.

The increasing height of buildings and their location in seismic zones of Ukraine demand heightened attention to the dynamic and seismic stability of all structural elements, including "non-structural components" such as facade systems. Traditionally, facades were considered secondary elements that do not affect the overall load-bearing capacity of a building. However, modern research convincingly demonstrates that damage to non-structural elements during earthquakes is a primary cause of significant economic losses, directly threatens the lives of occupants and passers-by, and can lead to the disruption of building functionality [1, 2]. Insufficient attention to the seismic stability of facades can lead to a cascading effect, where the failure of one element causes further destruction and creates danger. Therefore, the relevance of this study lies not only in increasing the reliability of an individual element but also in ensuring the overall seismic stability and functionality of buildings, which has direct socio-economic consequences and is critically important for the safety of settlements in seismic regions.

Analysis of Recent Research and Publications. Recent years have seen a significant increase in scientific interest in studying the dynamic and seismic behavior of facade systems. Research in this field covers both large-scale experimental testing and complex numerical modeling, aimed at increasing the stability and safety of these elements. The importance of these studies is underscored by constantly growing safety requirements and compliance with modern building codes in seismic regions.

Shake-table tests are one of the most effective and reliable methods for assessing the seismic behavior of non-structural elements, including facade systems. Research conducted by Samali and Abtahi (2016) [3] showed that facade systems have the potential to act as dampers, dissipating earthquake energy, thereby reducing vibrations of the main structure. Their work demonstrated that by optimally selecting materials for the stiffness and damping of brackets connecting the two facade shells, a significant portion of earthquake-induced energy can be dissipated [3].

Further works, such as Di Sarno's (2018) [4] research on the seismic behavior of hospital cabinets (an example of non-structural elements), also used shake-table tests. This study investigated dynamic properties and performance criteria, such as rocking and overturning, confirming the versatility of shake-table testing methodology for evaluating various non-structural components and their damage mechanisms [4]. In the context of ventilated facades, other studies have also included shake-table tests to assess seismic behavior, specifically for gypsum board partitions, demonstrating their positive in-plane and out-of-plane behavior [5]. This indicates a general trend towards experimental confirmation of the reliability of non-structural elements under seismic loads. The application of experimental methods, particularly shake-table tests, for evaluating the seismic behavior of non-structural elements is a clear trend in modern science. The complexity of the dynamic interaction of facade systems with the main structure requires physical tests to validate theoretical models. The availability of experimental data is critically important for confirming the adequacy of calculation models, which is a central aspect of the current study, where the calculation error does not exceed 7%. This emphasizes the high level of reliability and validity of the results achieved in this work.

Parallel to experimental studies, numerical modeling, particularly the finite element method (FEM), is widely used to analyze the stress-strain state of facade systems. For example, Samali and Abtahi (2016) [3] used three-dimensional models to study the dynamic response of facades acting as dampers. Their studies showed that imperfections in connection details can lead to significant stresses and facade damage under seismic loads, emphasizing the critical importance of designing fastening nodes [3].

Research on assessing the seismic behavior of pre-stressed glass facade systems (PFGFS) also actively uses FEM, both at the local connection level (3D FEM in ABAQUS) and at the global system level (simplified models in SAP2000) [6]. This work highlights the vulnerability of non-structural components and proposes innovative low-damage connections to increase the load-bearing capacity of facades [6]. Other works have also used finite element analysis to study the seismic behavior of composite walls with embedded steel elements [7]. In general, the application of FEM allows for detailed analysis of stress, deformation, and force distribution in complex facade systems, including fastening elements and cladding. An important aspect is the validation of numerical models using experimental data, as was done in the study of the energy efficiency of ventilated facades, where modeling results (TRNSYS) were compared with experimental data [8]. Numerical modeling allows for detailed investigation of facade behavior under loads [9-11]. However, its reliability is significantly enhanced when validated with experimental data. This creates a synergistic effect where each method compensates for the limitations of the other. The current study directly uses this approach, comparing calculations in Lira-CAD software with experimental data with an error of up to 7%. The combined approach (experiment + numerical modeling) is the most reliable for evaluating complex systems such as ventilated facades and allows for obtaining highly reliable results, which is critically important for responsible construction decisions.

Recent years' research consistently emphasizes the high vulnerability of non-structural elements, including facade systems, during earthquakes [1, 2]. Damage to these elements is a major cause of economic losses and can pose a threat to human safety [1, 2]. Samali and Abtahi (2016) [3] note that the facade, as a non-structural component with significant weight, can significantly affect the behavior of the main structure [3]. Projects such as ISCREANE (2023-2024) [2] aim to develop innovative methods and computational tools for the seismic assessment of non-structural elements, particularly for critical facilities (schools, hospitals) [2]. This includes the development of displacement-based methodologies and component fragility functions, allowing for more accurate prediction of their behavior and potential damage. The awareness of significant economic losses and life risks associated with damage to non-structural elements extends beyond purely engineering tasks, having direct social and economic consequences. This requires the development of new, more precise assessment methods. This need for innovation directly justifies the relevance of this study, which proposes precisely such a comprehensive approach to a specific type of facade system. Thus, research into the seismic stability of facades is not just a technical task, but part of a broader strategy to ensure the seismic stability of buildings and reduce risks to society.

Despite significant progress in research on the dynamic and seismic behavior of facade systems, unresolved issues remain regarding specific types of ventilated facade systems, their specific components, and their application under Ukrainian building codes. Existing studies often focus on general principles, certain types of cladding (e.g., glass panels [6], gypsum board partitions [5]), or specific regions (e.g., Kazakhstan [5]). However, a comprehensive assessment of the stability of the "KMD VF" system with RONSON 250×65×22 Busum facade tiles under vibrational and dynamic influences, as well as its applicability in seismic regions of Ukraine in accordance with DBN V.1.1-12:2006, remains insufficiently studied.

Although the general principles of seismic assessment of non-structural elements [1, 2] and methods of experimental and numerical studies [3-6, 8] are well developed, the specific characteristics of concrete facade systems, such as KMD VF with RONSON tiles, can differ significantly. Materials, structural solutions for fasteners (e.g., AD31T1 aluminum alloy, rivets, dowels), and their interaction under dynamic loads require individual assessment. Furthermore, the application of Ukrainian norms DBN V.1.1-12:2014 adds a unique regional context. This study fills an important gap by providing specific, validated data for a specific facade system under conditions compliant with Ukrainian building standards, which is critically important for practical application and construction safety in Ukraine.

Research Goal. To determine the stability of "KMD VF" ventilated facade systems with RONSON 250×65×22 Busum facade tiles under vibrational and dynamic influences. To determine the possibility of using this system in seismic regions of Ukraine, perform computational studies of the stress-strain state of the facade system elements and experimental laboratory tests of its fragment.

Research Objectives:

- Conduct an analysis of literature, initial data, and available technical documentation.

- Develop a methodology for the experiment, preparation of the test bench, and dynamic studies.
- Calculate a fragment of the facade system in the Lira-CAD software environment and compare the results with experimental data, draw conclusions regarding the adequacy of the calculation scheme and calculation methodology.
- Adopt the research and load-bearing capacity assessment methodology under seismic loads in accordance with [12-17].

Materials and Research Methodology. Ventilated facade systems are designed for thermal insulation and cladding of external enclosing structures, for new construction, reconstruction, and major repairs of existing buildings and structures.

KMD VF systems are multi-layered structures that include a load-bearing metal (aluminum alloy) frame (fastening system) attached to the base (load-bearing structures of the outer wall), an insulation layer, and a facade cladding layer attached to the elements of the load-bearing frame.

The KMD VF fastening system consists of parts and assembled units. By functional purpose, they can be divided into main parts (brackets, load-bearing posts), cladding elements (rivets, profiles), secondary parts (thermal breaks, auxiliary profiles), products for fastening brackets, insulation (anchors, facade dowels), parts for fastening the subsystem (bolts, nuts, washers, screws, pull rivets, self-tapping screws).

Basic parts and load-bearing elements of the fastening system are made of AD31T1 aluminum alloy DSTU B.V.2.6-30:2018 (6063).

During research and assessment of load-bearing capacity under seismic loads for KMD VF systems, numerical modeling using the finite element method is applied. Additionally, full-scale testing of key fastening nodes and system elements of a facade system fragment, secured on a vibration platform, is carried out to verify calculation models and refine material strength parameters under dynamic loads.

Research Results. Experimental tests of the facade system on a vibration stand were performed on a sample fragment with dimensions of 1000×900 mm (Fig. 1).

Vibration parameters – vibration displacements of the load-bearing vertical and horizontal elements of the facade system from an artificial vibration exciter were determined using the Vibran-2.0 vibro-analyzer.

Technical characteristics of the Vibran-2.0 vibro-analyzer:

- Vibration displacement measurement range – 0.01–10 mm;
- Operating frequency range – 0.5–1000 Hz.

To determine relative deformations and stresses in conjunction with the vibro-analyzer, a universal strain gauge station was used. Relative deformations were recorded in dangerous sections of the brackets and in steel profiles (at fastening points and in the middle of spans).

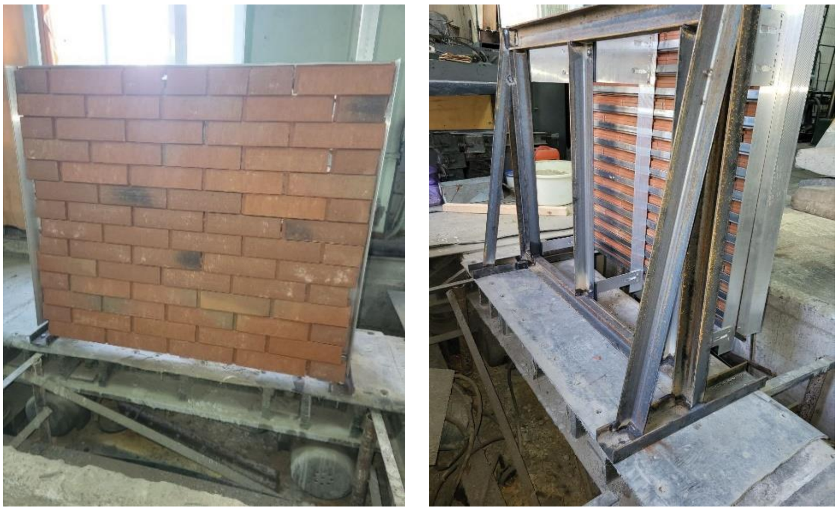

Fig. 1. Fragment of the facade system

The test results are presented in Table 1.

Table 1 – Test results of the facade system sample fragment

№	Sensor Placement	Unit of measurement	Value
1	Vertically, at the middle of the sample	mm	2.136
2	Vertically, at the middle of the sample	mm	0.085
4	Vertically, at the middle of the sample	mm	0.48
4	Horizontally, at the middle of the sample	mm	1.974
5	Horizontally, at the middle of the span	mm	0.098
6	Horizontally, at the middle of the span	mm	4.175
7	Stresses in brackets	MPa	28.5
8	Stresses in profile	MPa	83.1

To compare the results obtained from the response spectra, a dynamic analysis of the fragment was performed, and an analysis of the stress-strain state was conducted, including a check for potential clinker detachment.

A fragment of the calculation model for one facade system package is shown in Fig. 2. The calculation results are presented as stress fields for the most loaded section of the facade system. Stresses were determined using the Huber-Hencky-Mises criterion (Fig. 3).

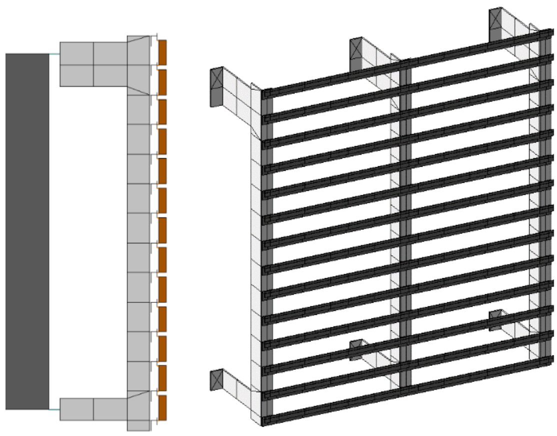

Fig. 2. General view of the test package

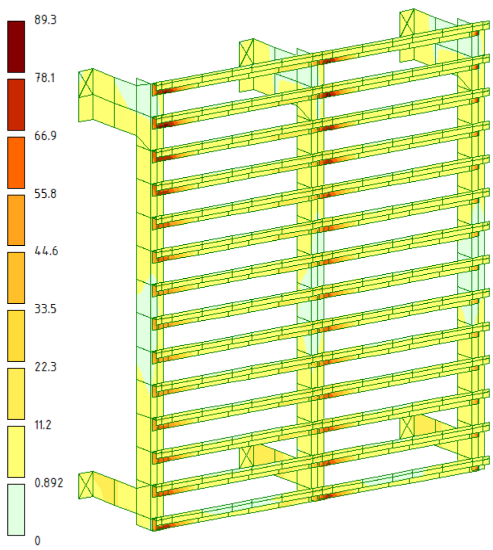

Fig. 3. Stress in fastening elements, MPa

It has been established that during the experimental tests, the facade system maintained its integrity, no individual tiles fell off, and the connection nodes of the elements remained reliable. The obtained stresses coincide with the calculation results, with an error not exceeding 7%.

Calculation of the Facade System for Seismic Load under Real-World Conditions

The research involves calculating the "KMD VF" ventilated facade system with RONSON 250×65×22 Busum facade tiles for conditions of combined operation with a multi-apartment residential building with a total height of 36 m.

Input Data for Seismic Load Calculation of the Facade System:

– Consequence Class (Building Responsibility Class) – CC-3.
– Wind Load – 370 Pa.
– Seismic Zoning Map – OSR-2004-S (1%).
– Soil Category by Seismic Properties – III.
– Seismicity of the Construction Site – 8.
– Design Seismicity according to Table 1.1 [17] – 9.
– Seismic Load Direction – X, Y, or Z.

Description of the Calculation Methodology. The calculation of the facade system, considering seismic effects, was performed in the Lira-CAD software environment using the spectral method in accordance with clause 2.3 [17] and [18-23].

To determine the design values of horizontal seismic loads on the facade system, a design scheme in the form of a spatial multi-mass elastically-deformable cantilever rod was adopted. This rod is rigidly fixed at its base, carries concentrated masses of weight Q_k, and undergoes oscillatory motion in one of the x, y, or z directions (Fig. 4, a).

The calculation model (Fig. 4, b) was constructed using volume finite elements (FE) to model the conditional building and clinker elements, shell FEs for brackets and spans, and also special FEs for modeling the connections between clinker and spans, spans and brackets, and brackets and the building. Separately, a fragment of the calculation model for one facade system package is shown in Fig. 5.

The design value of the horizontal seismic load S_{ki}, applied to point k according to the i-th natural vibration mode of the system, is determined by the formula:

$$S_{ki} = k_1 \cdot k_2 \cdot k_3 \cdot S_{0ki} , \qquad (1)$$

where: k_1 – coefficient accounting for inelastic deformations and local damage to building elements (Table 2.3 [17]) – 1.0 (damage or inelastic deformations are not allowed);

k_2 – structure responsibility coefficient (Table 2.4 [17]) – 1.0 (residential, public, and industrial buildings);

k_3 – floor coefficient – 1.3 (10 floors).

S_{0ki} – horizontal seismic load for the i-th natural vibration mode of the structure.

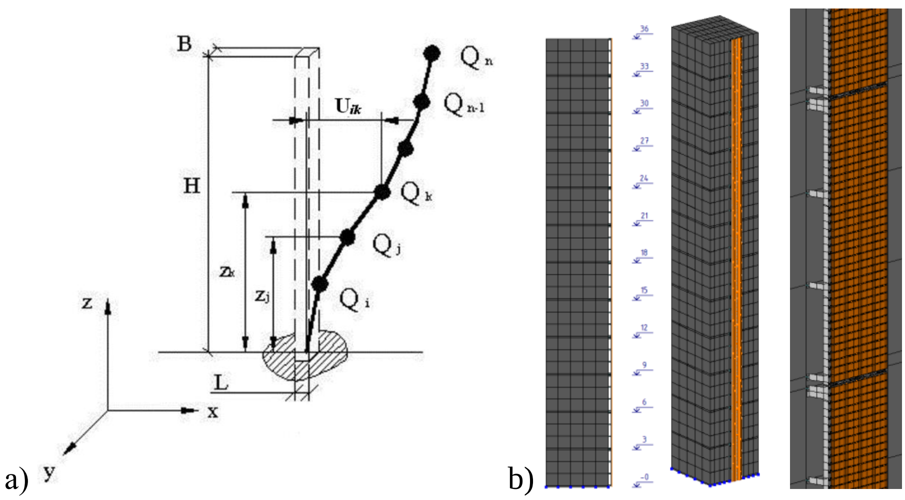

Fig. 4. Calculation scheme of the spectral method

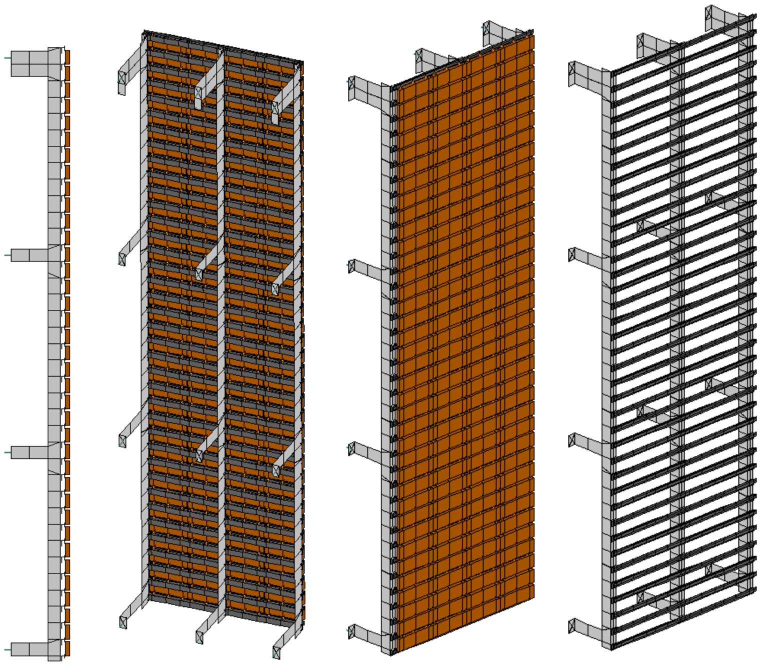

Fig. 5. General view of a model of one facade system package

Horizontal seismic load S_{0ki} according to the i-th form of natural oscillations of the structure, which is determined by the elastically deformed system by the formula:

$$S_{0ki} = Q_k \cdot a_0 \cdot k_{rp} \cdot \beta_i \cdot \eta_{ki} \,, \qquad (2)$$

where: Q_k – load corresponding to the mass determined by the program as concentrated at point k, taking into account the coefficients according to Table 2;

a_0 – relative acceleration of the soil (taken to be equal to 0.4);

k_{rp} – coefficient taking into account nonlinear soil deformation – 0.7 (for soil category III and seismicity 9);

β_i – spectral coefficient of dynamicity corresponding to the i-th form of natural oscillations of the structure (determined by the program);

η_{ki} – coefficient that depends on the form of the natural oscillations of the system or structure and on the location of the load (determined by the program).

Table 2 – Design load combinations

№	Coefficients of coupling				
	Own weight	Wind load	Seismic in the direction Y	Seismic in the direction X	Seismic in the direction Z
1	1.0	0	0	0	0
2	1.0	1.0	0	0	0
3	1.0	0	1.0	0	0
4	1.0	0	0	1.0	0
5	1.0	0	0	0	1.0
6	0.9	0.5	1.0	0	0
7	0.9	0.5	0	1.0	0
8	0.9	0.5	0	0	1.0

The calculation results are presented as stress fields for the most heavily loaded section of the facade system. Strength assessment was performed using equivalent stresses, determined with the Huber-Hencky-Mises energy theory (Fig. 6). Forces at the contacts between clinker and spans, spans and brackets, and brackets and the building are taken according to the corresponding special finite element of the model.

The summarized results are presented in Table 3. The load-bearing capacity indicators are presented as a coefficient, which indicates the degree of strength exhaustion. An allowable coefficient value of no more than 1.0 (or 100% exhaustion) is considered acceptable.

Table 3 – Summary of calculation results

№	Load-bearing capacity indicator	Estimated force, kg	Stress, MPa	Load capacity, kg	Design resistance, MPa	Exhaustion rate
1	Pull-out force of a dowel with a screw	44	-	150...500	-	0.30...0.10
2	Rivet pull-out force 3.2×8	4.2	-	25...45	-	0.17...0.10
3	Clinker separation force from the run profile	2.4	-	5.6	-	0.43
4	Stress in brackets	-	49	-	120	0.41
5	Stress in the profile	-	150	-	230	0.65

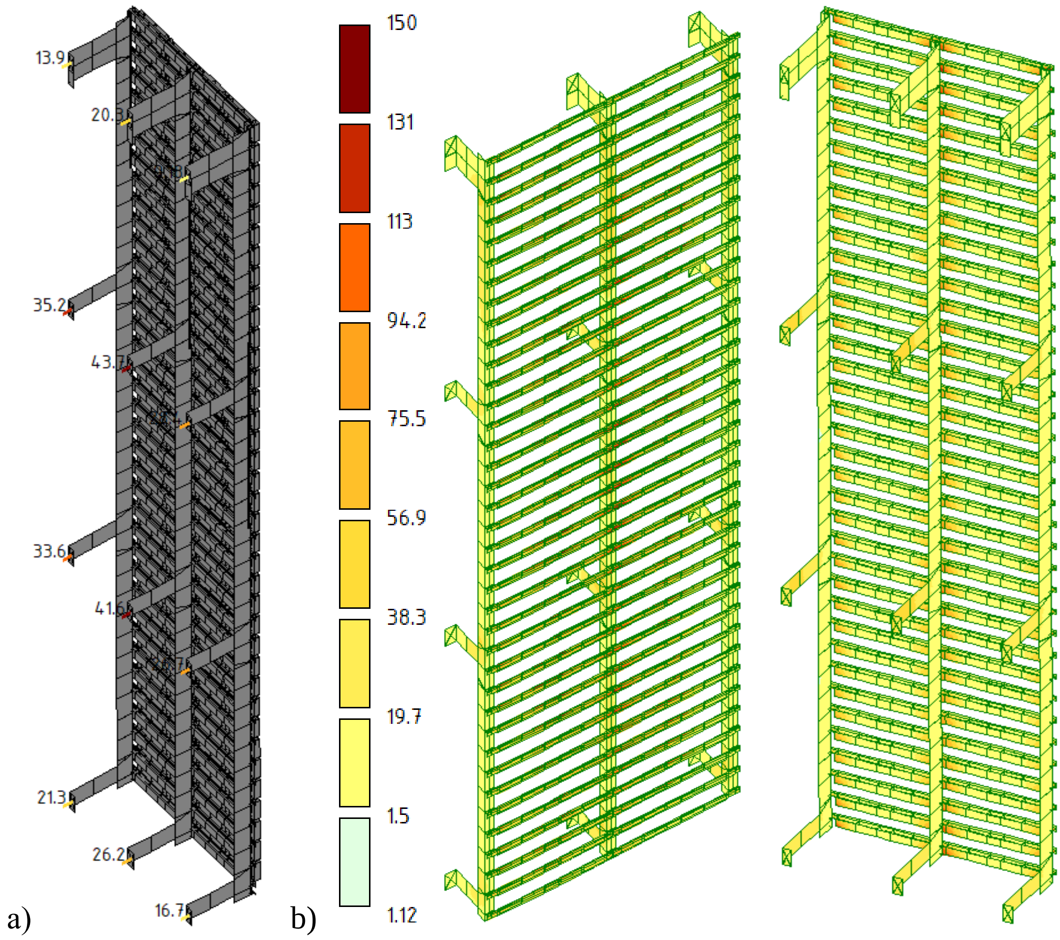

Fig. 6. Pull-out force of dowels with a screw (a), kg, stress in the fastening elements (b), MPa

Conclusions. Based on the comprehensive studies of the facade system, which included both experimental laboratory tests of its fragment and numerical modeling for seismic effects, the following key conclusions can be drawn:

1. Resistance to Vibrational and Dynamic Impacts. Experimental tests demonstrated the high

survivability of the facade system at a load level corresponding to approximately 60% of a 9-point seismic event. The system maintained its integrity, no individual tiles fell off, and the connection nodes of the elements remained reliable. The stresses obtained during the experiments coincide with the results of numerical calculations, with an error not exceeding 7%. This confirms the adequacy of the developed calculation scheme and methodology, which is the basis for the reliability of further predictions.

2. Seismic Resistance and Strength Margins. The spectral calculation of the facade system, operating jointly with a 36m high multi-story building, for seismic effects established that the exhaustion of the system's overall load-bearing capacity from a 9-point seismic event does not exceed 65%. This means that a significant strength margin of 35% is maintained. Furthermore, protection against the falling of individual tiles is ensured with a margin of 57%. These quantitative indicators demonstrate the high level of reliability of the system under seismic loads.

3. Feasibility of Application in Seismic Zones of Ukraine. Based on the obtained results, which confirm both experimental survivability and sufficient strength margins in seismic load calculations, it is concluded that the use of "KMD VF" ventilated facade systems with RONSON 250×65×22 Busum facade tiles is possible and advisable for construction in seismic zones of Ukraine. This solution is justified in terms of safety and compliance with building codes.

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ДОСЛІДЖЕННЯ СТІЙКОСТІ НАВІСНИХ ВЕНТИЛЬОВАНИХ ФАСАДІВ ДО ДИНАМІЧНИХ ТА ВІБРАЦІЙНИХ ВПЛИВІВ

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Анотація. Метою дослідження є визначення стійкості навісних вентильованих фасадів типу «KMD VF» з оздобленням фасадною плиткою RONSON 250×65×22 Busum під дією вібраційних та динамічних впливів, а також оцінка можливості їх застосування в сейсмоактивних регіонах України. Для цього було проведено розрахункові дослідження напружено-деформованого стану елементів фасадної системи та експериментальні лабораторні випробування її фрагменту.

В рамках дослідження виконано аналіз літератури та технічної документації, розроблено методику експерименту на вібраційному стенді з використанням віброаналізатора та тензометричної станції. Фрагмент фасадної системи розміром 1000×900 мм піддавався вібраційним впливам на вібростенді. Проведено чисельні дослідження фрагменту фасадної системи в ПК Ліра-САПР на дію вібраційних впливів, створених під час експерименту. Встановлено, що розбіжність результатів розрахунків і експериментальних даних не перевищує 7%.

Додатково виконано розрахунок фасадної системи на сейсмонавантаження для 36-метрової будівлі в умовах 9-бальної сейсмічності згідно з ДБН В.1.1-12:2014. При створенні розрахункової схеми була прийнята спрощена схема для моделювання будівлі із залученням об'ємних скінченних елементів і геометрично подібна до реальної конструкції фасадна система, побудована скінченними елементами оболонки. Схема навантаження передбачала використання спектрального методу.

Експериментальні випробування показали, що фасадна система зберігає цілісність, падіння плиток не відбувається, а вузли сполучення елементів залишаються надійними навіть при навантаженнях, що відповідають ~ 60% від 9-бальної сейсміки. Розрахунки на сейсмонавантаження підтвердили, що вичерпання несучої здатності системи не перевищує 65%, забезпечуючи 35% запасу міцності. Захист від падіння окремих плиток забезпечується із запасом 57%.

На підставі отриманих результатів зроблено висновок про можливість використання навісних вентильованих фасадів типу «KMD VF» з плиткою RONSON 250×65×22 Busum у сейсмонебезпечних районах України.

Ключові слова: навісні вентильовані фасади, сейсмостійкість, динамічні впливи, вібраційні впливи, фасадна плитка, експериментальні випробування, напружено-деформований стан.

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