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Fracture Mechanics of a Three-Layer Wall Panel Based on Two-Stage Concrete

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Abstract. Stress distribution in a three-layer wall panel based on two-stage concrete with rigid contact between the layers is modelled. The calculation is performed in ANSYS Workbench finite-element software. Values of failure criteria (principal stress and equivalent stress) are calculated near stress concentrators, i.e. edges separating the loaded and fixed faces of the panel. It is obtained that fracture begins at the boundary between the loaded and non-loaded layers of the structure. It is shown that the thermal insulation layer made of porous concrete in the center of the panel can carry part of the load acting on the bearing layer. So, structures made using the two-stage technology may withstand loads that are higher compared to that of panels with flexible ties. Moreover, it is shown that thermal resistance of the three-layer two-stage concrete panel is twice as high as for a single-layer panel of the same width. Therefore, the use of two-stage concrete panels is an effective measure for heat conservation in buildings.

Keywords: computer modeling, multilayer enclosing structures, strength, porous concrete, thermal insulation properties, finite-element analysis

Conflicts of interest. The authors declare that there is no conflict of interest.

Authors' contribution: *Syromyasov A.O.* — mathematical model, numerical calculations, text and illustrations; *Makarov Yu.A.* — mathematical model, text and illustrations; *Elchishcheva T.F.*, *Kozhanov D.A.* — data collection, verification of numerical results; *Erofeev V.T.* — supervision, problem statement, literature review. All authors read and approved the final version of the article.

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Механика разрушения трехслойной стеновой панели на основе каркасного бетона

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Аннотация. Моделируется распределение напряжений в трехслойной каркасной стеновой панели с жестким контактом между слоями. Для расчета использован конечно-элементный пакет ANSYS Workbench. Значения критериев разрушения (главного и эквивалентного напряжений) вычислены вблизи концентраторов напряжений, т.е. ребер, разделяющих нагруженные и закрепленные грани панели. Получено, что разрушение начинается на границе нагруженного и ненагруженного слоев изделия. Показано, что теплоизоляционный слой из крупнопористого бетона, расположенный в центре панели, способен участвовать в восприятии части нагрузки, приходящейся на несущий слой. В связи с этим несущая способность конструкций, изготовленных по каркасной технологии, существенно повышается за счет частичного нагружения теплоизолирующего слоя. Поэтому каркасная панель может выдерживать большие нагрузки по сравнению с панелями, имеющими гибкие связи. Кроме того, показано, что термическое сопротивление трехслойной каркасной панели вдвое выше, чем у однослойной панели такой же толщины. Тем самым использование каркасных панелей является эффективным средством сохранения тепла в зданиях.

Ключевые слова: компьютерное моделирование, многослойные ограждающие конструкции, прочность, крупнопористый бетон, теплоизоляционные свойства, конечно-элементный анализ

Заявление о конфликте интересов. Авторы заявляют об отсутствии конфликта интересов.

Вклад авторов: *Сыромясов А.О.* — математическая модель, проведение расчетов, создание иллюстраций, написание текста; *Макаров Ю.А.* — математическая модель, создание иллюстраций, написание текста; *Ельчищева Т.Ф.*, *Кожанов Д.А.* — сбор материала, проверка результатов расчета; *Ерофеев В.Т.* — научное руководство, постановка задачи, литературный обзор. Все авторы ознакомлены с окончательной версией статьи и одобрили ее.

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1. Introduction

The walls of a building are one of the main structural elements that carry loads and provide spatial rigidity and stability for the entire structure [1]. In addition to their load-bearing function, exterior walls also serve as enclosures, creating a favorable microclimate for the people inside the building. Therefore, effective materials and technologies are increasingly being used in their manufacture to ensure the strength and resistance of the products to aggressive environments and external loads [2], as well as sufficient thermal and sound insulation properties [3].

The required values for the load-bearing capacity and thermal resistance of building structures are determined based on various criteria, including economic ones [4]. It is known that walls made of prefabricated single-layer and multi-layer reinforced concrete panels are the most economical in terms of material consumption and construction technology.

Single-layer panels are sufficiently strong and technologically advanced, but their thermal insulation properties are insufficient for residential buildings in regions with cold climatic conditions. Therefore, such walls are currently used in regions with warm climate or in the construction of industrial and agricultural buildings.

Compared to single-layer panels, multi-layer panels are significantly more effective in terms of thermal performance. Such a panel consists of an insert (insulation) made of a material with low thermal conductivity, density, and strength [5], for example, mineral wool or glass wool, confined between the outer and inner layers. The outer layer, made of structural concrete, protects the insulation from external influences. The inner load-bearing layer is designed to carry the load transferred from the floor slabs; the insulation layer and the outer textured layer are attached to it by means of flexible ties, reinforced concrete ribs, or dowels.

However, along with their advantages, layered panels have significant disadvantages [6; 7]:

- short service life of the insulation and ties, which require anti-corrosion protection;
- lack of reliable connection of the insert to the concrete layers due to discrete arrangement of the ties;
- formation of cold bridges between the outer and inner layers due to high thermal conductivity of metal ties;
- uneven heat distribution in the wall and condensation in the interlayer space due to differences in thermal characteristics of the layers.

The consequences of these shortcomings are the exclusion of joint action of concrete layers in resistance to external loads, a tendency to develop significant shear strains due to deformation of the middle layer, and the short service life of such panels.

An alternative to such layered panels are three-layer wall panels based on two-stage concrete with a continuous connection between the layers, manufactured using a special technology [8]. Such products consist of two layers of dense expanded clay concrete, between which there is a middle layer of porous expanded clay concrete. The use of the latter type of concrete as insulation allows for the creation of materials with increased strength and stiffness and reduced thermal conductivity, as well as eliminating the structural disadvantages inherent in the three-layer panels with inserts. For example, the layer of porous concrete can effectively remove condensed moisture [9]. In operating conditions with biologically active environments, panels based on two-stage concrete are less susceptible to biodegradation [10; 11]. In turn, biostability contributes to the preservation of physical and mechanical properties of the construction products [12].

Porous concrete has reliable adhesion to the external concrete layers and is capable of resisting shear. Rigid contact between the layers allows the panel to be considered as one-piece, while panels with inserts are composite structures. The joint action of different types of concrete forming a single continuous section has been studied, for example, in [13; 14].

There are known calculation methods and additional hypotheses that take into account the aspects of deformation of three-layer structures [15]; in Russia, they are also regulated by state standards. Nevertheless, the behavior of these structures under different deformation modes is still insufficiently studied, which hinders their introduction into construction.

Computer modeling using CAE systems offers broad opportunities for studying this type of structure. In this article, such modeling is applied to the behavior of a loaded three-layer wall panel made on the basis of a two-stage composite using the technology described in [8] and implemented at OAO "ZhBK-1" in Saransk, Russian Federation.

The aim of the study is to test the hypothesis that the middle porous concrete layer not only acts as an effective insulator, but is also capable of carrying part of the load acting on the load-bearing layer.

2. Methods

2.1. Panel Geometry and its Physical and Mechanical Characteristics

The panel is modelled as a rectangular prism of length $l = 6$ m, height $h = 1.2$ m and total thickness of all layers $b = 0.4$ m.

The layers perform the following tasks:

- inner layer 1 is the load-bearing layer designed to carry load from the supported floor slabs; the thickness of this layer is $\delta_1 = 80$ mm;

- middle layer 2 is heat-insulating, designed to provide effective thermal protection for the building; its thickness is calculated based on the thermal properties of the materials used and the thermal insulation requirements for buildings of various types; in this study it is assumed to be δ_2 = 240 mm;
- outer layer 3 is protective and decorative; it protects the insulation from external climatic effects and creates architectural expressiveness of the structure; the thickness of this layer δ_3 is also equal to 80 mm.

The physical and mechanical characteristics of the layers are different and are shown in Table 1. The cross-sectional diagram of the panel is shown in Figure 1.

Poisson's ratio for all structural layers is the same and is ν = 0.18. Thermal conductivity is specified for type A service conditions of enclosing structures in accordance with the regulatory documents in force in Russia — design code[1].

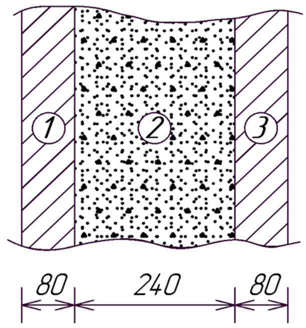

Figure 1. Sectional view of the three-layer wall panel
S o u r c e: made by Yu.A. Makarov.

The use of technologies such as fiber reinforcement and the like allows to obtain concrete, shear strength R_S of which is close to prismatic strength R_b. Therefore, it is assumed that $R_S = R_b$ for the layers of the studied panel.

Table 1

Physical and mechanical characteristics of the wall panel layers

ID and name of the structural layer	Layer material	Density ρ, kg/m³	Prismatic strength R_b, MPa	Initial modulus of elasticity E, MPa	Thermal conductivity λ, W/(m·°C)
1 — inner (load-bearing) layer	Dense concrete	1800	40	10000	0.483
2 — middle (thermal insulation) layer	Porous concrete	700	10	3500	0.206
3 — outer (decorative) layer	Dense concrete	1800	40	10000	0.483

S o u r c e: data on mechanical properties by V.T. Erofeev.

2.2. Verification of Panel Insulation Performance

First, the hypothesis that the studied three-layer panel is an effective heat insulator was tested. To do this, its thermal resistance was compared with the equivalent characteristic of a homogeneous panel of standard single-layer structure and of the same thickness.

The heat transfer resistance of a multilayer enclosing structure is determined by the following formula:

$$R_0 = 1/\alpha_B + \sum(\delta_i/\lambda_i) + 1/\alpha_H, \quad (1)$$

where α_B = 8.7 W/(m²×°C) and α_H = 23 W/(m²×°C) are the heat transfer coefficients of the internal and external surfaces of the enclosing structure, respectively; δ_i and λ_i are the thickness and thermal conductivity of the *i*-th layer of the wall.

In this analysis, the parameters of the panel layers were taken from Table 1; the thickness and thermal conductivity of a single-layer panel were assumed to be δ = 400 mm and λ = 0.58 W/(m×°C), respectively.

2.3. Modelling Panel Loading

Several options for loading the two-stage concrete panel were considered in the study, and the one that provides the maximum linear load that the panel can withstand without failure was selected.

[1] SP 50.13330.2024. Thermal performance of buildings. Intr. 2024–06–16. Moscow: Russian Standardization Institute, 2024. 70 p.

In the model it was assumed that the bottom and both side faces of the panel were fixed, and the width of the restrained strip $b_0 \geq \delta_1$; in other words, the load-bearing layer and (partially) insulation layer are fixed. A downwards normal force (pressure) *P* is applied to the section of the panel selected in this way; moreover, self-weight *G* is also applied to the structure (Figure 2).

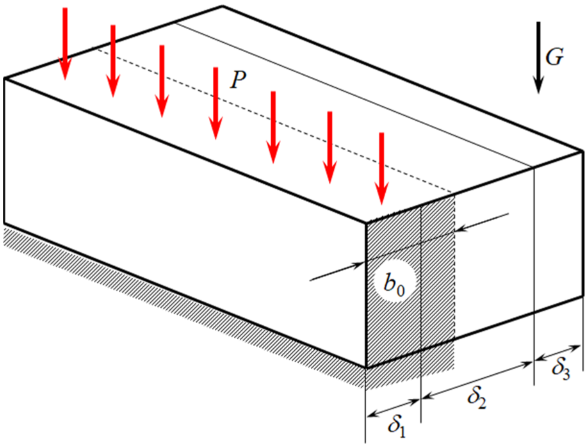

Figure 2. Panel loading diagram
S o u r c e: made by A.O. Syromyasov.

The described methods of restraint and loading simulate the interaction of the panel with its neighbors below and to the side (through a layer of cement mortar), as well as supporting the floor slab.

The method of computer modeling of three-layer two-stage concrete panels under such loads is described in detail in [16]; since in this study not only the load-bearing layer but also the thermal insulation layer is loaded, minor adjustments had to be made to it. The method takes into account the fact that, due to only a part of the panel cross-sectional area being loaded, its material is in a combined stress state, and the critical strength parameters cannot be described by a uniaxial stress state model. Therefore, when evaluating the load-bearing capacity of the panel, several strength criteria are used, the values of which are examined at several different points.

The ANSYS Workbench finite element software, installed under license on the Mordovia State University computing cluster, was used for the calculations. Figure 3 shows one of the calculation results — an overall distribution pattern of equivalent stress (von Mises) on the external surface of the panel loaded by $P = 4.55$ MPa and with loaded layer thickness $b_0 = 200$ mm.

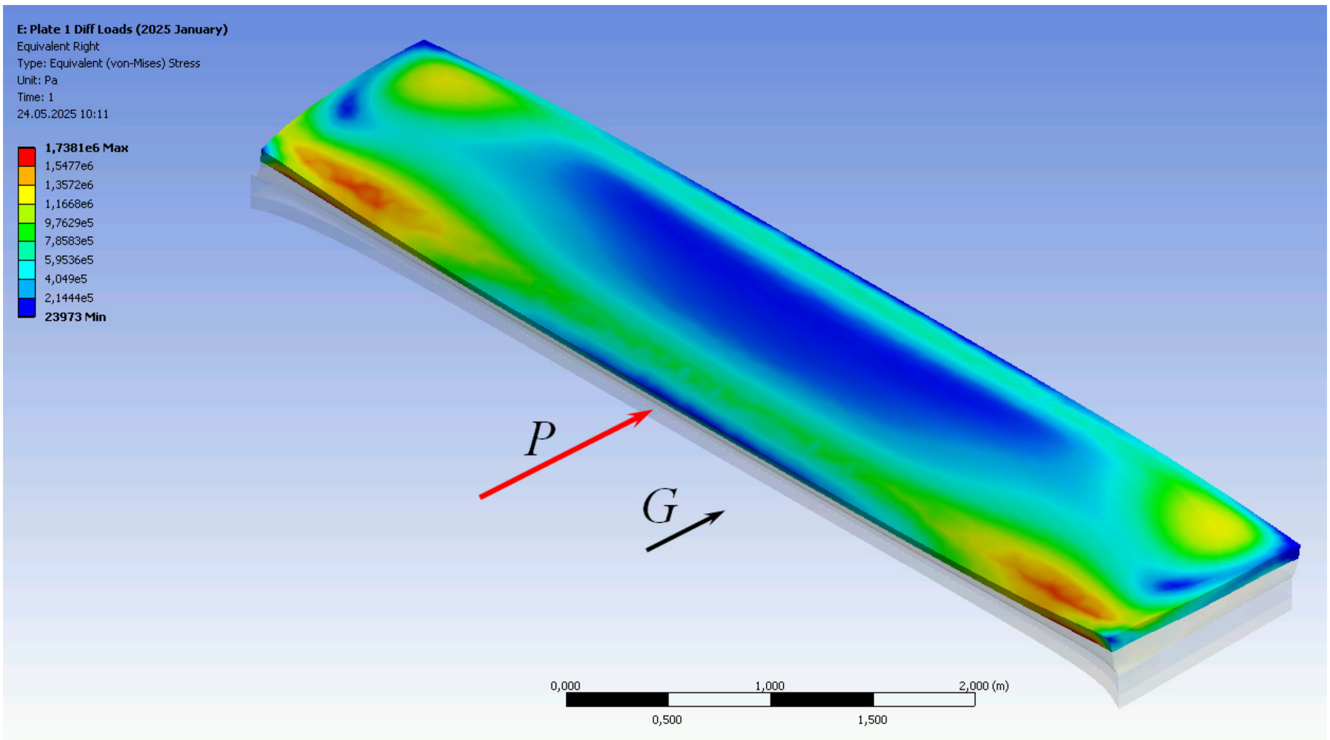

Figure 3. Distribution of equivalent stress on the panel surface
S o u r c e: made by A.O. Syromyasov in ANSYS Workbench software.

The panel is most likely to fracture in the area of stress concentration, i.e., near two symmetrical edges **e** and **e**’, where the fixed side faces are adjacent to the loaded upper face. Therefore, internal stresses in the panel should be calculated along the control line segment L, which is located at a distance of 1 cm from the side and 1 cm from the upper face parallel to edge **e**. Particularly, the principal normal stress σ_1 and equivalent stress σ_{eq} according to the Huber — Henky — von Mises theory was calculated.

3. Results and Discussion

When calculating the thermal insulation properties of the panel in (1), it was found that the thermal resistance of the single-layer structure $R_0 = 0.848$ m^2·°C/W, and for the proposed three-layer structure $R_0 = 1.655$ m^2·°C/W. Thus, the use of multi-layer enclosing structures based on two-stage concrete instead of standard single-layer panels of the same thickness significantly reduces heat loss in buildings.

The graphs of σ_1 and σ_{eq} along segment L provide a general idea of the stress distribution inside the panel. Thus, Figure 4 presents the graph of σ_{eq} at $b_0 = 200$ mm and $P = 4.55$ MPa. The value at $x = 0$ corresponds to the interior boundary of the load-bearing layer, and the value at $x = 400$ mm – to the exterior face of the panel. At other values of b_0 and P, the graphs of σ_1 and σ_{eq} look similar.

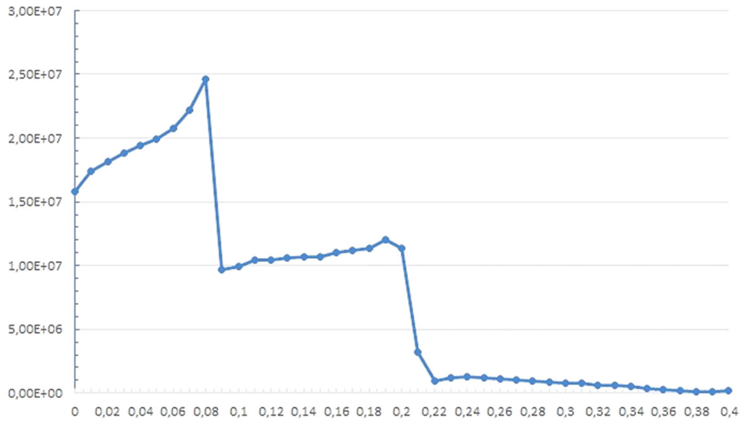

Figure 4. Distribution of equivalent stress (von Mises) along the control line
S o u r c e: made by A.O. Syromyasov.

Two peak values of the failure criterion are reached at $x = \delta_1$ and $x = b_0$, i.e. at the boundary between the load-bearing and insulation layers, and at the boundary between the loaded and non-loaded layers.

Based on the calculation results, the stress arising in the outer layer is many times smaller than that in the inner layer. This implies that the loads in the outer layer can be disregarded. Indeed, the mechanical characteristics of the two layers are identical, which means that failure will occur sooner in the more intensely loaded inner layer.

Based on the above, the failure criterion for the studied panel is considered to be the fulfillment of at least one of the following conditions:

- at the boundary between the load-bearing and insulation layers (on the *load-bearing* layer side), principal normal stress σ_1 exceeds the prismatic strength R_b of the load-bearing layer *or* equivalent stress σ_{eq} exceeds the value of $1.15R_b$;
- at the boundary between the load-bearing and insulation layers (now on the *insulation* layer side) stress σ_1 exceeds R_b of the insulation layer *or* equivalent stress σ_{eq} exceeds the value of $1.15R_b$ of the same layer;
- at the boundary between the loaded and non-loaded regions (inside the insulation layer) $\sigma_1 > R_b$ *or* $\sigma_{eq} > 1.15R_b$, in which case the prismatic strength of the insulation layer is considered.

In doing so, the values of σ_1 and σ_{eq} are examined at three points P_1, P_1' и P_1^*, located at the intersection of line L and the boundaries of the aforementioned layers.

To investigate the influence of the thermal insulation layer on the magnitude of fracture stress and the load-bearing capacity of the structure, the panel was loaded with an increase in the total width of the loaded strip b_0 from 80 to 200 mm with a step of 40 mm. The results of the analysis are presented in Table 2.

Table 2

Relationship between of the fracture stress and the width of the loaded layer

Type of criterion	Critical value, MPa	Value, MPa (b_0 = 80 mm)	Value, MPa (b_0 = 120 mm)	Value, MPa (b_0 = 160 mm)	Value, MPa (b_0 = 200 mm)
		P = 9.04 МПа / MPa	**P = 5.78 МПа / MPa**	**P = 5.15 МПа / MPa**	**P = 4.55 MPa**
$\sigma_1(P_1)$	30	***30.77***	22.99	22.47	21.22
$\sigma_{eq}(P_1)$	34.5	34.17	27.50	26.37	24.62
$\sigma_1(P_1')$	10	9.92	8.23	8.01	7.62
$\sigma_{eq}(P_1')$	11.5	12.10	10.16	9.53	8.80
$\sigma_1(P_1^*)$	10	–	9.55	9.85	***10.01***
$\sigma_{eq}(P_1^*)$	11.5	–	***11.49***	***11.47***	11.36
$\tau_{xz}(P_1)$	–	7.03	8.86	8.69	8.14
$\tau_{xz}(P_1^*)$	–	–	2.65	2.72	2.57

S o u r c e: obtained by A.O. Syromyasov using ANSYS Workbench software.

P indicates the pressure at which the panel fails. For every b_0, criteria values close to or exceeding the maximum allowable values are highlighted in bold. For reference, shear stress values τ_{xz} at the layer boundaries are also given; as can be seen, their values are quite far from the critical value R_b.

The data in Table 2 shows that failure always occurs at the boundary between the loaded and non-loaded layers – at point P_1^* (when b_0 = 80 mm it coincides with P_1).

By increasing width b_0 the value of failure pressure P drops. However, it is not the value of P itself that plays a key role, but rather the maximum allowable load per unit length $f = Pb_0$ that can be resisted by the panel. The value of f depending on the width of the loaded layer is presented in Table 3.

Table 3

Relationship between the linear load and the width of the loaded layer

b_0, mm	P, MPa	$f = Pb_0$, kN/m
80	9.04	723.2
120	5.78	693.6
160	5.15	824.0
200	4.55	910.0

S o u r c e: obtained by A.O. Syromyasov using ANSYS Workbench software.

Thus, supporting floor slabs by a 200 mm wide strip instead of standard 80 mm allows to increase the maximum allowable load by more than 25% — from 723.2 kN/m to 910.0 kN/m.

Multilayer panels with inserts lack such properties, since their insulation layers are made of materials that cannot carry loads. All loads in such panels are resisted exclusively by a thin inner load-bearing layer.

Further improvement of the load-bearing capacity of products based on two-stage concrete can be achieved, for example, by modifying the cement binder with polymer compounds [17; 18], finely dispersed fillers [19; 20], and nanoparticles [21; 22].

4. Conclusion

Thus, the article examined the behavior of a loaded three-layer panel manufactured using the two-stage technology. The interaction of the panel with adjacent panels was modeled by fixing three of its side faces, with pressure applied to the upper face reflecting the load carried by the panel. The study tested the assumption that the middle (thermal insulation) layer of the two-stage concrete panel is capable of partially resisting the external forces. It was necessary to determine at what loads the panel would begin to fracture and where exactly this fracture would begin.

The ANSYS Workbench software, which implements the finite element method, was used for calculations. Special attention was paid to calculating the failure criteria near the edges, along which the loaded face "joins" with the fixed ones. The principal and equivalent (according to von Mises) stresses were selected as such criteria; it was assumed that fracture would begin if at least one of them exceeded the "dangerous" value. The magnitude of the applied pressure and the width of the loaded part varied in the calculations.

The obtained results allow to draw the following conclusions:

1. The panel fractures at the boundary between the loaded and non-loaded layers near the edge, which is the stress concentrator.
2. When the width of the loaded part increases, the failure pressure may decrease due to the fact that the load is applied to the less strong insulation layer. However, the linear load at failure increases due to the increase in the area of the section that carries this load.
3. It follows from the previous conclusion that by partially loading the thermal insulation layer, the load-bearing capacity of the panels manufactured using the two-stage technology can be significantly increased compared to panels containing mineral wool or other thermal insulation inserts, since such inserts cannot be loaded.

In addition, the article shows that three-layer panels based on two-stage concrete have twice the thermal resistance of standard single-layer panels of the same thickness, making the use of two-stage products an effective method of heat conservation.

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