Impact of the Fire and Acoustic Protection on the Composition of Lightweight Wood-based Cladding Envelopes in the Construction of Apartment Buildings in Passive Standard

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Abstract
The aim of the paper is to analyze structural systems of wood-based buildings and their applicability in the construction of apartment buildings in terms of fire safety. It also describes the optimization of the material base of thermal insulation and cladding materials in terms of fire and acoustic insulation and optimization of insulation and cladding materials in terms of sustainable development. The result is assessment of their suitable application in the construction of apartment building depending of the fire height and Comparison of their physical parameters in terms of thermal and acoustic insulation.

1. Introduction
Wood is an organic material unique to its appearance and mechanical properties, depending on the conditions in which the tree has grown. The excellent static and environmental properties are the great advantage of using wood as a building material. The limitation in the use in buildings is its flammability and limited fire resistance. Thermal properties, flammability, wave resistance and bulk density have a significant impact on the choice of thermal insulation, not only the financial possibilities of the investor and his attitude to natural or chemical materials.

Modern timber construction systems designed for passive buildings are optimized in terms of statics in the context of fire resistance of the weakened cross-section and in terms of thermal and acoustic comfort in the proposed premises. The paper deals with the analysis of alternative solutions of cladding envelopes for three wood-based load-bearing structural systems in terms of their fire and acoustic insulation in apartment buildings. Alternative solutions are analyzed in accordance with the legislation in the context of the Strategy 2020 requirements.

2. Structural systems of wooden buildings
Each type of timber construction system has different levels of the fire resistance. Depending on the type of load-bearing construction system, they are primarily divided into framed structure in construction: Balloon–Frame, Platform-Frame, and their use is limited by their fire height, depending on the type of a construction, max on 2-3 floors. Timber frame structures are currently the most widely used structural systems for low-rise buildings. A wooden stud construction can be interrupted at the ceiling or continuous over the entire height. If the stud construction is interrupted at the ceiling, then the studs are independent on each storey (Platform –Frame). The second of the possibilities is Balloon-
Frame; the studs extend from the foundation to the rafters without interruption entire the height. Wooden panel buildings are similar to this prefabricated system.

The second system is the prefabricated buildings. Their advantage over the other systems is quick assembly. They are produced as small-sized ones with a width of 1.2-1.8 m or large-sized with a length of 12.0 -16.0 m. The frame of the panels is made of spruce or fir wood with cladding of wood-based panels or plasterboard with thermal insulation. The second option is solid wood-glued panels. CLT panels, also known as KLH, are made from PEFC certified spruce wood. The panels consist of 3-7 layers of single-layer boards glued together under pressure.

The panels are always insulated from the exterior, plastered or visible on the interior. Their surface finish is directly dependent on the fire safety requirements of the building.

Timber skeleton constructions are the counterpoint of the buildings consisting of solid wood and frame constructions. In solid timber and timber frame structures, the load-bearing structure is linear, and loadings from ceilings and roofs carry load-bearing exterior and interior walls. In skeleton systems, the studs transmit the load from the ceilings and roofs to the foundation. System disposition of building is more variable and can be applied for multi-storey buildings in terms of static load and fire resistance. Wooden elements of the skeleton construction are made of glued-laminated timber with recessed connecting steel elements. The building envelope is usually designed as a self-supporting lightweight sandwich panel, e.g. from a wooden frame structure whose air cavity is filled with thermal insulation. The external envelope panel may be designed in front of the support structure or recessed between the columns. The ideal solution in terms of thermal protection and elimination of thermal bridges is to mount it in front of a skeleton support construction. In terms of fire protection, the building envelope panels are generally designed as fire-resistant structures with the required fire resistance EI or EW wooden-based as partially open fire areas, this depends on the thickness of the thermal insulation and its combustibility class.

![Figure 1. The most frequently used structural systems in timber buildings: a) timber skeleton system, b) panel system – solid wood construction, c) timber frame structural system.](image)
3. Legislative restrictions on the applicability of structural systems of apartment buildings in terms of fire safety

The fire safety requirements for wood-based apartment buildings directly depend on their fire height and the type of construction. The definition of the structural component of a building depends on the flammability of the insulating and cladding materials used on the supporting timber elements. The fire height depends on the number of fire floors. Depending on these two parameters, the requirement for minimum fire resistance of load-bearing and fire-separating elements is determined for apartment buildings.

In the past, Slovak standards allowed for two-storey buildings for housing and accommodation. In July 2017, fire safety requirements changed after 40 years. Revision of the standard STN 92 0201-2: Fire safety of buildings allows to design wooden buildings intended for housing and accommodation, which meet the criteria of a mixed construction system at the level of five above-ground floors.

In this case, all partitioning and supporting structures must be covered with a non-combustible material. Contact and ventilated façade cladding systems must comply with A1 or A2 reaction to fire class. The cavities must be completely filled with thermal insulation with reaction to fire class A1 or A2, which must also be used in the facade thermal insulation system.

The temperature of thermal degradation of thermal insulations has to be minimal 100 °C. The insulation must be placed without any settlement option or falling of parts after coating failure. The level of 12 m is the limit for fire belts necessity. They cannot consist of wooden construction components. The fire resistance of loadbearing and separating constructions is from 45 to 60 minutes for five-storey timber buildings [1].

If the wooden construction is visible, or if the thermal insulation within the cavities or the cladding material does not meet the requirements, the building is of combustible construction system. The apartment buildings have then limited fire height of three storeys. The fire resistance of the load-bearing and fire-separating elements is from 60 to 90 minutes.

![Figure 2. Maximum permitted fire height of apartment buildings depending on the construction system: a) Maximum fire height of apartment buildings with timber structural system – mixed construction system, b) Maximum fire height of apartment buildings - combustible construction system](image)

4. Acoustic insulation requirements for building envelope

They are directly derived from the noise emission in the built-up area at a distance of 2m from the perimeter cladding.
The intensity of the noise in front of the facade is determined by acoustic measurement by adding the intensities from all sources in the area. The most common source of noise is traffic, municipal or production operations.

The assessment of the sound insulation of the external cladding and the values of their required sound insulation are given in table 2 of STN 73 0532 for the living environment. In areas with increased noise emission, airborne sound insulation for nighttime operation is generally critical. Interpolation of requirements according to the actual equivalent sound pressure level A in front of the facade is permissible.

The resulting airborne sound insulation of the cladding is directly dependent on the area and acoustic insulation of the cladding structures. It can be calculated according to the relation (1): \( R'w, f \geq R'w \) (requirement in accordance with table 2 in STN 73 0532). [3]

\[
R'w, f = 10 \cdot \log S_f - \sum_{k=0}^{n} S_i \cdot 10^{-10Rwj - k3}
\]  

(1)

Where:
- \( S_f \)… total perimeter wall area viewed from room [m²]
- \( S_i \)… partial surface of perimeter wall [m²]
- \( R_{wj, j} \)… weighted sound reduction index of perimeter wall element [dB]
- \( k_3 \)… minor path correction factor; heavy circuit. walls \( k_3 = 1 \text{ dB} \); light walls \( k_3 = 2 \text{ dB} \).

5. Requirements for the thermal performance of buildings in a sustainable standard

The current requirements for thermo-technical characteristics of buildings are listed in STN 73 0540-2/Z1 z 8/2016, which set the following course of building constructions improvement. Since 2016, the buildings need to be built in ultra-low-energy standard, i.e. the maximal energy consumption 40.7 kWh/m² in energy class A. After 2020, the requirements for energy consumption will be stricter, i.e. the specific maximal energy consumption 20.4 kWh/(m²·a), the energy class A0.

The energy consumption for heating is influenced by the thermal parameters of the building constructions. Requirements for cladding envelope and building openings are defined in legislation. The heat transfer coefficient \( U (\text{W} / (\text{m}^2 \cdot \text{K})) \) is used to determine the cladding envelope parameters. A well-insulated cladding is not sufficient to achieve a passive building standard, but other aspects must be included in the design: building orientation with active use of solar gains, using triple glazing for building openings, controlled ventilation with heat recovery, or installing an energy efficient power renewable source. [4]

As stated in requirements for heat transfer coefficient values \( U \) for building constructions according to STN 73 0540-2, normalized values \( (U_{N}) \), had to be achieved after 2013. Since 2016, it is necessary to reach the values marked as recommended \( (U_{r1}) \). After 2020, they will be valid as normalized values for nearly zero-energy buildings (indicated as target recommended values \( U_{r2} \)). [5]

Values valid after 2020:
- flat roof – \( U \leq 0.1 \text{ W/m}^2 \cdot \text{K} \), which represents \( R = 9.9 \text{ (m}^2 \cdot \text{K})/\text{W} \),
- exterior wall – \( U \leq 0.15 \text{ W/m}^2 \cdot \text{K} \), which represents \( R = 6.5 \text{ (m}^2 \cdot \text{K})/\text{W} \).

6. Optimization of the exterior wall structure in terms of fire protection

The choice of thermal insulation in sandwich wood structures is conditioned by its thermal insulation efficiency, combustibility class, durability and the possibility of recycling after life cycle of construction. The cladding envelope with the load-bearing wooden structure must be designed without condensation zone at the joints of the timber elements. In terms of hygienic requirements, the thermal insulation layers and their physical parameters in the cladding envelope must be designed to maintain a minimum surface temperature above the critical surface temperature of the must at each point of the interior wall, depending on the environmental boundary and type of heating. The type, thickness and closure of the thermal insulation in the wall structure has a major influence on the resulting fire resistance of the wooden panel as well as the category of the construction element and the subsequent construction system.
The construction of wooden buildings can be considered as a mixed construction system if the all fire dividing and supporting constructions ensuring the stability of the building are only of type D2, while:

- the supporting components of these structural elements have TRO (fire reaction class) at least D-s2, d0
- all cavities in these components are completely filled with TRO A1 or A2 components with a melting point at least 1000 °C
- fastening of components in the cavities of these construction members prevent them from moving and falling out; it is valid even if the exterior component of the construction member loses its protective function.

The construction elements of type D2 do not increase the fire intensity during the required fire resistance, because building materials or elements with flammability class other than A1 or A2 are enclosed with building materials or components with flammability class A1 or A2 so they do not ignite and do not release heat during required time of the fire resistance. The flammable materials and components enclosed within the D2 component must not reach the flash point during the required fire resistance period; if not clearly defined, a flash point of 180 °C is considered. The time required to reach the flash point can be demonstrated experimentally or by calculation. [6]

It follows that the supporting wood elements must be protected by claddings with flammability class A1 or A2. The thermal insulation in the air cavities as well as exterior insulation must be non-flammable with a melting point above 1000 °C and its minimum bulk density should be higher than 30 kg/m³. These physical parameters are based on mineral wool or glass fiber thermal insulation. The structural elements of type D3 may ignite and increase fire intensity during the required fire resistance and cannot be considered as D1 or D2 structural elements, figure 3.

**Figure 3.** Examples of cladding envelope in buildings with mixed construction system D2 - variant a, b; Examples of cladding envelope in buildings with combustible construction system D3 - variant c, d; A1 – non-combustible construction element, B-F – combustible construction element.

**Table 1.** The example of an optimized lightweight cladding envelope in terms of fire protection in mixed structural system in the context of the Strategy 2020 requirements – **Variant 1.**

| Structural arrangement           | λ  (W/m.K) | ρ  (kg/m³) | Combustibility class | Material thickness (m) | \( U \leq 0.15 \) (W/(m².K)) | m' (kg/m²) |
|----------------------------------|------------|------------|----------------------|------------------------|-----------------------------|-------------|
| Interior cladding               |            |            |                      |                        |                             |             |
| Alternative 1. - Cetris board   | 0.29       | 1150       | A2                   | 0.016                  | 22.4                        |             |
| Alternative 2. - SDK             | 0.22       | 750        | A2                   | 0.015                  | 13.2                        |             |
| Alternative 3. - Mgo board       | 0.25       | 1000       | A1                   | 0.015                  | 6.4                         |             |
| Installation wall – Woodsil      | 0.038      | 37         | A1                   | 0.06                   | 4.44                        |             |
Table 1. The example of an optimized lightweight cladding envelope in terms of fire protection in mixed structural system in the context of the Strategy 2020 requirements – Variant 1 - continued

| Structural arrangement | λ (W/m·K) | ρ (kg/m³) | Combustibility class | Material thickness (m) | U ≤ 0.15 (W/(m²·K)) | m’ (kg/m²) |
|------------------------|-----------|-----------|----------------------|------------------------|----------------------|-----------|
| OSB board + vapor barrier | 0.13      | 650       | E                    | 0.012                  |                      | 2.10      |
| Multi-layer insulation |           |           |                      |                        |                     |           |
| Alternative 1. MW Woodsil | 0.038     | 37        | A1                   | 0.26                   | 0.093                | 4.44      |
| Alternative 2. Blown insulation - SUPAFIL LOFT | 0.034     | 35        | A1                   | 0.26                   | 0.08                 | 3.15      |
| Alternative 3. Foam glass | 0.044     | 130       | A1                   | 0.26                   | 0.10                 |           |
| OSB board               | 0.13      | 650       | E                    | 0.012                  |                      | 2.10      |
| Facade insulation –MW   | 0.038     | 50        | A2                   | 0.08                   |                      | 4.44      |
| Exterior plaster        | 0.99      | 1600      | A1                   | 0.01                   |                      |           |

The time to break the timber and wood-based fire-protecting boards is the time when the temperature of the surface that is not exposed to fire rises by more than 500K. For F-type plasterboards, 15 mm thick, with increased cohesion of the core at the high temperature, it can be determined according to the relation: $t_{bp} = 1.9 \cdot \xi \cdot t_p$ [7] The time to break F-type plasterboards is $1.9 \cdot 1 \cdot 15 = 28.5$ min.

The time to break non-flammable insulation materials, more than 20 mm thick with mass weight above 30kg/m³ that remain compact to 1000 °C, can be calculated according to the relation:

$$t_{bp} = 0.07 \cdot (t_{ins} - 20) \cdot \sqrt{\rho_{ins}}$$

where:
- $t_{ins}$ … thickness of the insulation material in mm
- $\rho_{ins}$ … mass weight of the insulation material in v kg/m³.

In terms of fire protection, flammability is crucial and fire resistance of the cladding material of the load-bearing timber structure on the thermal side the fire stress and the flammability class of the thermal insulation in the air cavity. [8]

Table 1 gives the examples of variant solutions - the use of cladding materials and thermal insulation for the building with a mixed structural unit with fire resistance REI 30-60 min. The design of the thermal insulation thickness is optimized in terms of energy performance according to the Europe 2020 Strategy.

7. Optimization of the exterior wall structure in terms of acoustic protection

As a rule, there are two types of perimeter of wooden wall constructions - simple walls of massive and multiple constructions of light sandwiches. In terms of acoustic insulation, for example, CLT wall panels can be considered as simple structures; figure 3, variants of solution 2b, 4d. Single-layer structures vibrate as a whole. They consist of one building material or several layers of similar materials having similar acoustic properties. In these cases, the apparent sound reduction index (airborne sound insulation) increases with their basis weight and generally increases with the frequency of the incident sound energy. In the coincidence area, the airborne sound insulation decreases, the reason being the interference effect of mass inertia and bending rigidity of the structure. In single wooden structures, the effect of bending stiffness is disadvantageous since their basis weight is usually less than 100 kg / m². This means that the critical frequency position is about 200 to 1000 Hz. The frequency response of these structures is characterized by the fact that in the so-called. The sound-insulating area (range 100 to 3150 Hz) includes all areas of frequency response of sound transmission. In the area of resonance influence, the sound insulation of the structure is small. It is therefore appropriate to regulate the design of the construction of the position of the self-resonance area so that $f_0 < 100$ Hz. In the mass impact area, the frequency domain is in the range of about three times the resonance frequency $f_0$ to one third of the
critical frequency of the $F_{CR}$ (critical frequency) wavelength coefficient. It is typical for structures with low bending stiffness. The bond between the structure and the environment is optimally small in this area, the speed and wavelength of the free bending waves in the structure is less than the speed and wavelength of the excitation of the sound waves falling from the air. Theoretically, the bending wave does not occur in the structure and the airborne sound insulation does not depend on the material composition of the structure, but only depends on the frequency and the basis weight of the structure.

The law of weight is done, while the weight is ideally used. Due to the accidental impact of sound waves, doubling the basis weight increases the airborne sound insulation by 6 dB. The weight of a simple timber structure is optimally utilized when this area is contained in the soundproofing area as much as possible. The consequence of this theory is higher sound insulation of more massive walls.

The area of influence of the wave coincidence is characterized by a decrease in airborne sound due to the increasing influence of the bending stiffness of the structure. It is above the critical frequency of the $F_{CR}$ wave coincidence. The rate of air sound reduction depends on the material parameters of the structure. In general, with increasing wall thickness, the $F_{CR}$ wave coincidence shifts to lower frequencies. The projection of the length of the obliquely incident sound wave coincides with the length of the bending wave in the wall. The wall is oscillated with a deflection equal to the deflection of the air particles of the incident sound waves. The wall emits sound energy to the protected space, the intensity of which is reduced only by losses caused by internal wall damping. For small thickness walls, the effect is visible at high frequencies (above 2000 Hz). [9]

Building acoustic insulation of perimeter wall (var. 2) and with composition: SDK – 15 mm fibre reinforced gypsum board, 90 mm CLT panel Stora Enso, SDK – 15 mm fibre reinforced gypsum board, 75 mm mineral wool with a thin-layer render is $R'w = Rw - k1 = 56-8 = 48$ dB in terms of the manufacturer's measurements. [7] Since the value of the maximum required airborne sound insulation is 48 dB in the area with high noise emission at nighttime, the given design is suitable for the construction of apartment buildings in terms of acoustic insulation.

In terms of acoustic insulation, respectively multiple constructions consisting of two simple constructions separated from each other by a continuous separation layer of negligible weight material (air, alternatively acoustic insulation – e.g. MW); see figure 3, solution variants 1a and 3c. The wooden double structure is a lightweight dividing wall in terms of building acoustics, consisting of two flexurally resilient layers mounted on an intermediate support structure ideally circumferentially and acoustically away from the support elements by resilient seals. In the frequency response of the double structure, in addition to the influence of frequency domains specific to simple structures, the effects of frequency domains that are specific to them also apply. Effect of mass-compliance-weight resonance where sound insulation degrades to a value comparable to simple construction. It is appropriate to regulate the position of the resonant frequency by combining the basis weights of the two simple elements with the thickness of the separation layer so that $f_r < 100$ Hz. The resonant frequency decreases with increasing basis weight of both simple elements and with increasing thickness of the separation layer.

a. **The effect of separation of partial simple elements** follows the area of resonance influence. The maximum increase in sound insulation (compared to a value corresponding to two single elements at zero distance) is achieved at approximately four times the resonance frequency. The value of this maximum increases in direct dependence on the thickness of the separation layer.

b. **The standing wave region** (wave resonance pole) in the separation layer manifests itself by reducing the sound insulation of the double structure compared to the value of the mutual separation of the partial simple elements. The standing wave is formed by folding the direct sound wave (transferred to the separation layer) with the sound wave reflected on the inner surface of the partial simple elements. The frequency of the first sound insulation minimum in this area depends on the speed of the longitudinal sound waves in the separation layer material and the thickness of the separation layer. The area of standing wave influence overlaps with the area of separation effect. With increasing thickness of the separating layer $d$ [m], the standing wave effect area penetrates into the soundproofing frequency band. The negative influence of the standing wave region in the air separation layer is effectively controlled by filling the gap with a porous absorber whose thickness $h \geq 0.5$ d. In the case of cladding, this is generally the thermal insulation between the supporting timber structures. Its absorption is directly dependent on its wave resistance. Ideally, materials with low wave resistance - mineral wool and the like - are ideal.
Acoustic insulation of external claddings is expressed by a single-digit quantity for building practice building airborne sound index, which is about 4 to 8 dB lower than the one measured in the laboratory, is determined by the formula:

\[ R'_w = R_w - k1 \]  

(3)

where:

\( k1 \) - correction, dependent on the sound propagation side paths; \( k1 = 4 \) to \( 8 \) dB recommended values for lightweight structures in skeletal, steel or wooden structures (board, gypsum board, wooden walls, etc.).

8. Conclusions

With increasing thermal insulation, thickness in terms of optimizing the energy performance of buildings, the use of non-flammable thermal insulation with a melting point above 1000 °C also increasing the resulting fire resistance of these cladding envelopes. In low-rise panel buildings as well as in prefabricated frame systems, the fire resistance of wooden load-bearing elements of external claddings is sufficiently ensured in optimising the selection of thermal insulation on the interior side. The airborne sound insulation of simple wood-based structures is influenced by wave coincidence and self-resonance. In the case of double constructions, there are also other specific influences such as the bulk density of the wood, the thickness of the joints, the quality of the surface coating, the dimensions of the components and the quality of the implementation.

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