

Hydrothermal performance of the external wooded frame wall structure reinforced with ballistic panels

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Abstract. In recent years construction of bullet resistant walls has become very common not only for military buildings but also for public and residential buildings. The existing wall structure in those buildings is reinforced by ballistic panels. However, in the cold climate regions external application or installation of the ballistic panels can cause interstitial water vapor condensation. Also, an incorrect application of such panel on the internal surface can lead to an insufficient drying of the structure during the summertime. This paper presents an analysis of thermodynamic properties of ballistic panels. For this purpose, laminated and non-laminated ballistic panels were examined. Thermal conductivity features such as water vapor permeability were evaluated in laboratory conditions. Based on gathered results the DELPHIN simulation software and THERM calculation tools were used to analyze the thermal resistance of wooded frame wall reinforced with ballistic panels. The obtained results were validated under controlled environment. Temperature and moisture measurements were performed inside the tested wooded frame structures reinforced by ballistic panels under different internal and external air parameter fluctuations.

1 Introduction

Military buildings encompass a range of unclassified and specially designated structures for military personnel and military operations. Such buildings require special approach and versatile building design background already at the planning and design stage, which is a common challenge for those involved, as the requirements for structural stiffness and overall endurance are very specific and often not standardized for this type of building category. One of the key safety parameters for these buildings is blast and bullet resistance of the external building envelope. Clearly these parameters could not be compromised by other parameters such as energy efficiency, indoor air parameter etc. The blast and bullet resistance is especially important for buildings situated in an active military area. For military buildings located in civil areas, stricter requirements on energy efficiency can be established while the ballistic resistance requirement may be lowered to a certain extent. Since the military personnel training and regular duties require carrying weapons, the bullet resistant walls may prevent any personal injury or accidental firearm deaths. The difficulty in terms of planning and design is added by long-term vision to integrate energy efficient measures in such structures and eventually reduce the energy consumption, which according to some studies may result in up to 65% energy savings [1,2].

In addition, it should be noted that it's not only military buildings that pertain risks of accidental firearm deaths and injuries. Also, public buildings where local

security officers are wearing weapons should have a protection against accidental gunshots.

Nowadays the construction of temporary shelter for refugees has increased. In such areas, there is a risk of mass shootings.

Due to the above listed factors the demand for bullet proof structures is increasing across the world. Such structures are well suited for modular solutions which allow fast on-site mass construction without compromising construction quality and minimizing construction failure.

The growing terrorism [3] threats across the world also play an important role in the design of civil buildings and living areas. The study also simulates people evacuation during indoor mass shooting accident. However, it doesn't take into account bullet resistance level of the wall structure. Bullet resistant external wall as well as internal partitions can significantly reduce injury risks during terrorist attacks or mass shooting accidents. Usually ballistic panels are used to reinforce regular civil constructions. One of the innovative solutions is to use reinforced modified concrete [4] [5]. Such massive constructions are normally used for permanent structures including transportation hubs [6]. Many manufacturers of the ballistic panels already offer a bulletproof wall solution. However, to meet energy efficiency requirement, the exiting solutions can be improved by the application of thermal insulation layers. This requires the use of extra load bearing structure, weather barriers and water vapor control layers.

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According to Latvian Cabinet Regulation No. 1001 Regulations Regarding the Acquisition, Registration, Recording, Possession, Transportation, Conveyance, Carrying, Sale of Weapons and Ammunition and Possession of Collections of Weapons, the external walls of the weapons' depository shall be equivalent in durability to a 200 mm thick reinforced concrete wall or brick external wall the thickness of which is not less than 510 mm. This significantly reduces the applicability range of the wood frame structures for military applications and limits mass production of the building with specific requirements on bullet protection.

This paper presents several solutions on how the wooden frame structures can be reinforced by ballistic panels. Prefabricated wooden structure can be used no only for new construction but also for retrofitting of the existing buildings.

2 Thermo dynamic properties of ballistic panels

Within the scope of this study a 12 mm thick ballistic panel made of aramid was examined. This panel complies with UL752 level 5-6 requirement for ballistic resistance, ensuring the minimum protection criteria attributed to military structures (army facilities have to comply with L5 to L8 bulletproofing requirements) [7], [8], [9]. Polyaramid fibers make the armor lighter and more reliable in comparison with other materials [10]. The laminated and non-laminated samples were tested. Laminated panels are used directly for interior finishing of outdoor facade decoration. Ballistic panel can be classified as external or internal placement.

Evaluation of the thermal performance includes practical measurement of thermal conductivity and water vapor permeability. These are the two main parameters which should be considered in order to evaluate thermal performance of the wall assembly as well as the risk of interstitial condensation. Long term interstitial condensation occurrence without sufficient drying in summertime can negatively affect the overall performance of the whole structure and material properties.

Performed measurements have shown that thermal conductivity of ballistic panels varies from 281.45 mW/mK to 282.24 mW/mK. Average result is 0.282 W/mK.

Determination of vapor permeability coefficients for the material was performed in accordance with ISO 12572: 2016 "Hygrothermal performance of building materials and products — Determination of water vapour transmission properties — Cup method". Five samples of non-laminated and three samples of laminated panel structures were examined.

Table 1. Vapor diffusion on non-laminated ballistic panels

| Sample Nr. | Vapor permeability g/m ² /24H | Standard deviation WBTR | Vapor diffusion thickness Sd m |
|------------|--|-------------------------|--------------------------------|
| 1 | 1.8 | 0.505 | 0.505 |
| 2 | 1.9 | 0.1 | 19.157 |
| 3 | 4.7 | 0.539 | 7.507 |
| 4 | 3.5 | 0.601 | 10.181 |
| 5 | 2.4 | 0.589 | 14.979 |

Average water vapor permeability of the analyzed samples is 3.11 g/m²/24H and average water vapor diffusion thickness – 10.467 m. vapor diffusion thickness varies from 0.505 m to 19.157 m. The lowest result was excluded from further analysis. Remaining samples of the vapor diffusion thickness varies from 7.507 m to 19.157 m, with an average - 13 m.

Data for laminated panels is shown in Table 2.

Table 2. Vapor diffusion on laminated ballistic panels

| Sample Nr. | Vapor permeability g/m ² /24H | Vapor diffusion thickness Sd, m |
|------------|--|---------------------------------|
| 1 | 1.3 | 16.179 |
| 2 | 0.7 | 29.392 |
| 3 | 0.8 | 25.116 |

Average water vapor permeability of analyzed samples is 0.92 g/m²/24H and average water vapor diffusion thickness – 23.565 m.

As it can be seen laminated aramid panels have higher vapor diffusion thickness than non-laminated panels. This can cause a higher interstitial condensation risk in case of an external placement.

3 Wooded frame construction

As stated earlier, external wooded frame wall construction reinforced with ballistic panels can be used for both – the construction of new buildings as well as retrofitting of the existing buildings.

In general, facades can be classified into two major groups: rendered facades or double facades. Classic rendered facade does not allow installation of extra protection materials such as ballistic panels. For this purpose, ventilated facade should be used. Double faced facades with ballistic panels can be used also for construction of new buildings where one of the wall's layer is load bearing. This would be the most optimal solution in terms of internal moisture control. The wooded frames or metal fasteners (Figure 1) can be used to place ballistic panels.

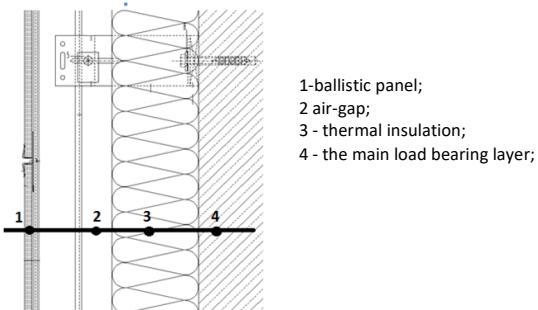


Fig. 1. Double faced facade with ballistic panel and metal fasteners

The aforementioned solution has a number of flaws such as poor tightness of connections of the ballistic panels and the weight of the panels which introduces extra mechanical stress on the load bearing elements. In addition, construction time for such facades is significantly longer and it requires a higher number of on-site labour workers in comparison to classic rendered facades. One new solution that is currently widely promoted on market is modular retrofitting [11] [12]. This approach is very well suited for military needs where construction time, quality, reliability as well number of civil workers involved in construction process plays an important role for technology selection. Previous studies have indicated that wood-frame structures meet the requirements for application in cold climate [13]. Cross-laminated timber wall structures [14] are suitable for cold climate regions as well. However, majority of the studies have analyzed wooden frame walls with ventilated air layers on the external side. This solution can be easily adopted and reinforced for the use of external ballistic panels (Figure 2).

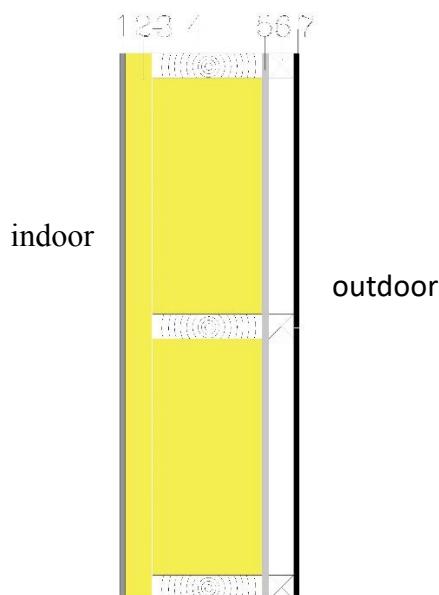


Fig. 2. Ventilated wooden frame wall (1- dry wall; 2 – thermal insulation/wooden frame; 3 – water vapor barrier; 4 - thermal insulation/wooden frame; 5 - wind barriers; 6 – ventilated air layer; 7 – ballistic panels)

This solution can be used for the construction of permanent structures and for the retrofitting of the existing buildings. In order to increase the construction of temporary structure, the economically feasible and fast solution should be introduced [15]. One of the alternative solutions is SIP panels or wood frame structures without ventilated air gap. SIP can substantially reduce construction time, and therefore, man hours cost, i.e., a study of one conventional framed structure and one SIP structure found that the SIP structure was constructed with 65% less on-site labour. If properly designed, the modular house or warehouse made of composite structural insulated panel can withstand blast loads and have only minor, i.e., repairable damage in case of an accident or an explosion [16].

The main drawback for the application of this solution in cold climate regions is high vapor diffusion thickness of ballistic panels. It can cause an intensification of interstitial condensation and slowdown the rate of self-evaporation during summer period.

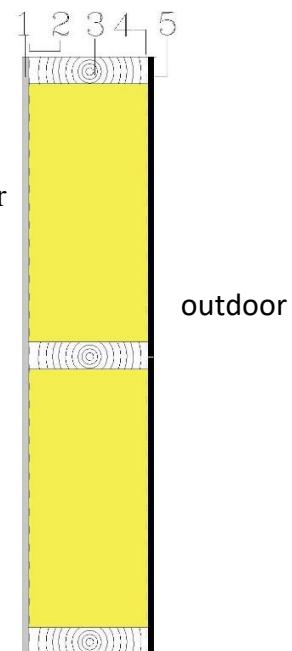


Fig. 3. Simplified wall solution for temporary building construction ((1- dry wall (internal side); 2 – vapor barrier; 3 – thermal insulation/wooden frame; 4 – fiber glass mesh; 5 – ballistic panels (external side)))

Such structures have high share of thermal bridges which can be minimized by long span wooden frame carcass.

The fiber glass is necessary to keep thermal insulation in place during production process and also during panel replacement and maintenance. Another study related to this topic [17] proved that 3 mm-thick glass fiber can increase the projectile impact resistance capacity of SIP to wind velocity 32 m/s. This factor also plays an important role relating to the placement of the fiber glass close to an external surface.

4 Hydrothermal evaluation of wall equipped with exterior ballistic panels

In scope of this study a sandwich panel with mineral wool and different water vapor layers was evaluated. In the first case a smart vapor barrier was employed; in the second case – a regular polyethylene film barrier was used. In both cases mineral wool was used as thermal insulation layer. The structure with a smart vapor barrier was also tested in a climatic chamber for further DELPHIN simulation validation. Ballistic panel was placed on external side. A demo wall was built in climatic chamber (Figure 4). The temperatures and relative humidity sensors were placed indoor, outdoor and at an interface between thermal insulation and ballistic panel.



Fig. 4. The demo wall

The demo wall represents wooden carcass construction with different materials. Buffer thermal insulation layer was used to minimize negative effect of thermal bridge at climatic chamber and tested demo wall connection.

The initial DELPHIN simulation was carried out based on the measured indoor and outdoor air temperature, as well as the relative humidity in climatic chamber. During the testing indoor air parameters were controlled and measures.

Gathered results on relative moisture simulations were compared with DELPHIN simulations. Figure below shows comparison of measured data and simulation results of a wall equipped with smart vapor retarder. Vapor diffusion thickness is humidity variable: 0.25 - >25 m.



Fig. 5. Measured and simulated relative humidity at interface between thermal insulation and ballistic panel

In general, measured and simulated data have a similar layout and the discrepancy is in the ballpark of 7% - 10%.

This discrepancy could be explained by relatively short measurement period. Thus, the developed model was used for further general evaluation of hydrothermal behavior. Figure 6 shows relative humidity fluctuation between thermal insulation and ballistic panel of wall equipped with smart vapor retarder from January till September (including). This allows to make a preliminary evaluation of moisture accumulation and drying potential during winter/summer period. Note: January is statistically the coldest month in Latvia.

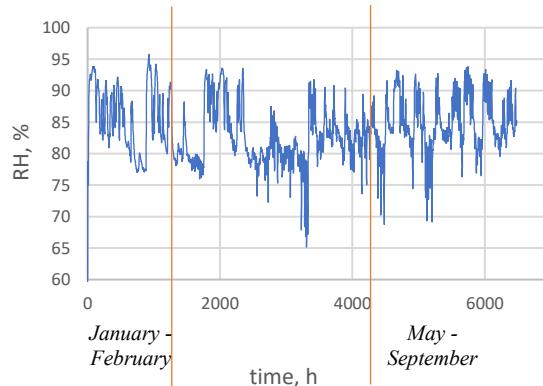


Fig. 6. Simulated relative humidity at interface between thermal insulation and ballistic panel (case: smart vapor retarder)

To run a simulation on ballistic panel's hydrothermal behavior based on the DELPHIN model, ASHRAE IWECC Weather File for Riga was used. Data on indoor air relative humidity and temperature fluctuation was generated according to ISO 13788 as premised without mechanical HVAC systems. As it can be inferred from fig. 6., the peak relative humidity reaches 96% in coldest winter months (Jan-Feb). The most active drying process occurs in spring when both the outdoor and indoor air relative humidity is slightly lower. Nevertheless, high permanent relative humidity (>80%) can cause mold growth on wooden frame [18].

Next figure presents simulation for case where a regular vapor retarder is used instead of smart vapor retarder. Two options were compared within this study: vapor diffusion thickness Sd 2,3 m and Sd 35 m.

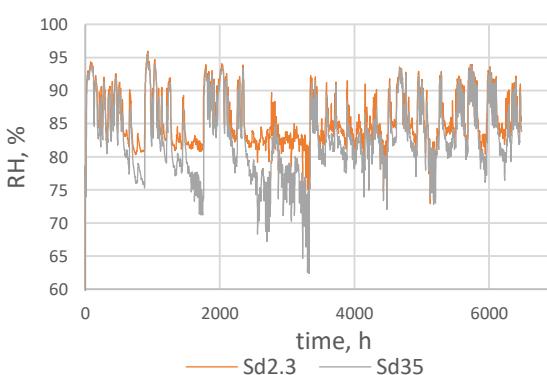
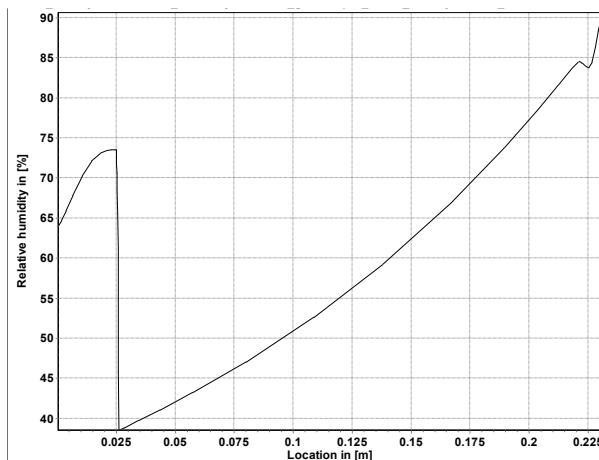
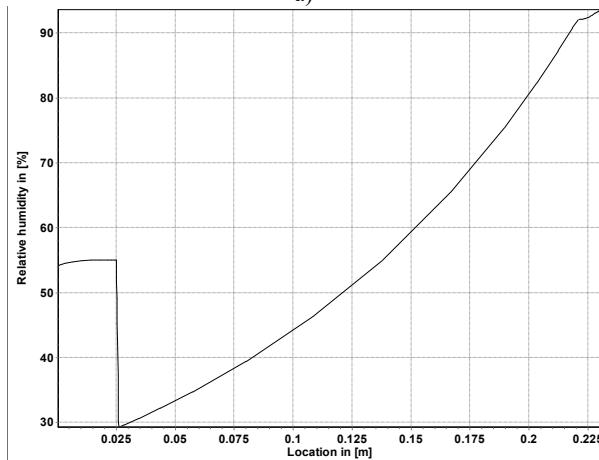


Fig. 6. Simulated relative humidity at interface between thermal insulation and ballistic panel

As it can be seen maximal relative humidity reached same values as in case with smart water vapor retarder. However, vapor retarder Sd35m ensure better performance in spring season.



a)



b)

Fig. 7. Relative humidity distribution across construction (a – Sd 35; b – Sd2.3)

As it can be predicted relative humidity at interface between internal gypsum board and vapor retarder is higher than that for the smart water vapor retarder and reaches 74%. Study [19] has shown that at 20°C and 76% RH no mold growth was detected on any dry board during the 17 weeks period. The same study shows that growth of fungi on gypsum board is moderate at 90% RH and 20°C. Relative humidity distribution inside construction is shown in figures 8 and 9.

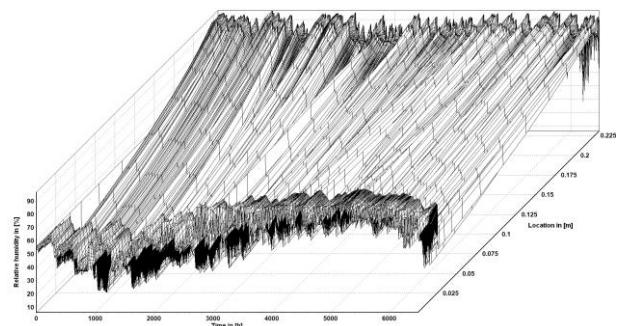


Fig. 8. Relative humidity distribution inside construction with vapor barriers Sd75 m

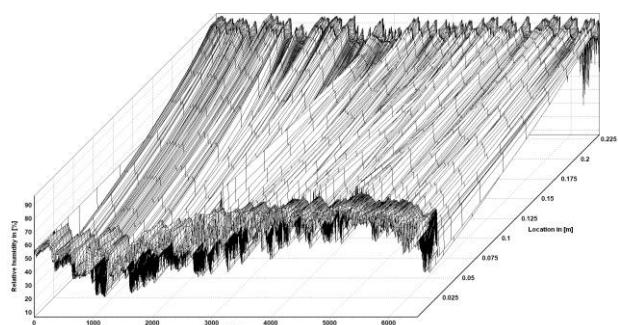


Fig. 9. Relative humidity distribution inside construction with smart vapor barriers

One of the options to reduce construction time and simplify technical solution is to use sandwich construction where ballistic panels are used on both sides without any vapor retarder and OSB sheeting. Results for this case are shown in figure 10.

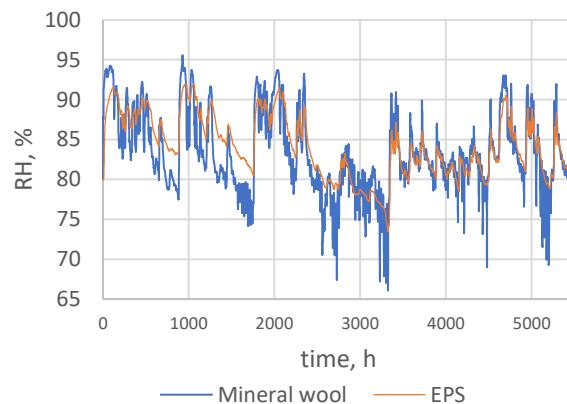


Fig. 10. Relative humidity distribution in SIP at interface between thermal insulation and external ballistic panel

In general, mineral wool shows slightly better results. However, this material is not common for SIP panels due to its limited ability to glue it with exterior panels.

Conclusions

This study presents a preliminary analysis of hydrothermal performance of the external wooden frame wall structure reinforced with ballistic panels. As noted earlier, the examined ballistic panel structure meets the

minimum ballistic resistance criteria for military facilities – complying with level 5-6, according to UL752 classification. However, this work will be continued further to examine the hydrothermal properties of the ballistic panels of higher UL752 rating (either by increasing the material thickness or adding/replacing different materials to the current panel structure).

Gathered results have shown that ballistic panels do not have a homogeneous structure and measured vapor diffusion thickness varies across a relatively wide range: from 0.505 m to 19.157. The possible cause for that is the homogeneous distribution pattern of aramid fibers. Such high measured vapor diffusion thickness can lead to interstitial condensation occurrence at an interface between the thermal insulation layer and the ballistic panel. This is particularly common for assemblies without ventilated air layer.

Performed measurements in laboratory conditions showed good correlation with DELPHIN hydrothermal simulations.

All the examined water vapor retarders (smart, Sd2,3 and 35) have shown rather similar results. Maximum relative humidity level at the interface between thermal insulation and the ballistic panel peaked at 96%, which can cause condensation issues related to mold growth in the long term. Smart water vapor retarder ensures significantly lower relative humidity level at the interface between the internal gypsum board and vapor retarder.

The study results suggest that wooden frame structures without a ventilated air layer could be used with external ballistic panels in applications to ensure fast on-site assembly and construction speed. However, to elaborate on the findings of the current study, future studies focusing on mold growth on wooded carcass are recommended.

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