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TIMBER FRAMED WALLS LINED WITH GYPSUM PLATES UNDER FIRE

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ABSTRACT

Building regulations require fire rating for partition walls under standard fire exposure. New eco building solutions are becoming popular and, in particular, the light timber framed walls. The fire rating of this building element depends on fire testing. Finite element approximation can be used, when models are validated from previous experimental tests. This investigation presents the validation model from a full-scale assembly, using one gypsum board on each side and several solid timber studs. The charring rate in the wood studs is an important predictor for the fire performance of the wall and as well the temperature of the unexposed surface. This investigation also predicts the temperature field in other key points, such as the points located in interface between the studs and gypsum board, for the onset of charring. Finally, the fire resistance is also considered by means of the simplified method (improved model). This models seems to under predict and over predict the results. There is a good approximation between the numerical model (Hybrid –FEM) and the experimental test used for validation, which allowed for a parametric analysis, testing the variation of the gypsum thickness and the thickness of the cavity. The dimension increase of the wood stud does not provide almost any change on the fire resistance of the assembly (insulation), but provides significant modification on the residual area for load bearing capacity.

Keywords: partition walls, fire resistance, timber frames, Gypsum plasterboard.

INTRODUCTION

Light timber framed walls are becoming popular structures used on buildings, for load bearing and partition walls. The assemblies are made with solid stud wood members, that may be protected by a variable number of gypsum boards or other lining materials. The cavity formed by the lining plates may be filled with insulation materials. The fire resistance of this structural elements mainly depends on the protection of the cladding system. The fire resistance may be verified for the load bearing capacity (R), insulation (I) and integrity (E), usually using experimental standard tests EN1363-1 [1] ISO834 [2], depending on the type of timber framed walls, EN1365-1 [3] and 1364-1 [4]. The fire rating usually used for these construction materials are defined by the European standard for fire classification of construction products and building elements EN13501-2 [5]. This European standard proposes a relative high number of completed minutes for loadbearing walls with fire separating function REI (15, 20, 30, 45, 60, 90, 120, 180, 240, 360) and for partition walls EI (15, 20, 30, 45, 60, 90, 120, 180, 240). The safety level is then selected by each European country, using its own national regulation system. The annex E of EN1995-1-2 [6] can be used for predicting the fire resistance of partition walls, using simple calculation methods, assuming that requirements with respect to integrity

(E) are assumed to be satisfied when the requirement to insulation (I) has been satisfied and panels remain fixed to the timber frame on the unexposed side. This solution method is based on the component additive model, since the fire resistance is obtained by the summation of the fire resistance defined by each layer (protection, cavity and insulation), see Figure 1.

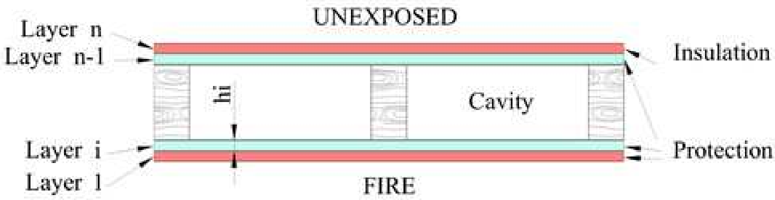


Fig. 1 - Timber framed wall with basic layers for protection and insulation

This method considers the influence of adjacent materials on the thermal performance of each layer. According to Andrea Frangi *et al.* [7], this design method was developed based on a reduced number of experimental tests, therefore covering a limited cases of timber framed walls. The improved design model presented by Andrea Frangi *et al.* [7] is based on a large number of small scale tests, developed with different material thicknesses, positions and number of layers. This method was based on seventeen experimental results developed for testing the protection materials used for cladding [8], based on the experimental procedure for the determination of fire protection ability EN14135 [9] and fire classification of wall EN13501-2 [5].

This investigation presents a two-dimensional parametric analysis, based on a hybrid finite element method. The model was firstly validate with the experimental test 6, developed by Takeda and Mehaffey [10]. The time history for the temperature of the cavity was based on the previous experimental tests, developed by the authors, in partition walls using one gypsum plate [11] and two gypsum plates [12], both using a three stud LSF. This time history takes in consideration the most important failure events on the cladding material, such as gypsum cracks gypsum fall off, opening gaps or any combustion process, when using single or double layers of gypsum plates.

FIRE RESISTANCE TESTS AVAILABLE

According to EN1363-1 [1], every specimen should be tested in furnace following the procedures for testing walls. The load bearing capacity (R) is the ability of the timber framed wall to withstand exposure to fire, under load, using one fire exposed surface for a period of time, without any loss of structural stability. The criteria that provide for the evaluation of the load bearing capacity of axially loaded elements are specified by the actual displacement limit value (contraction C = h/100 mm, where h is the element height) or by the rate of vertical displacement (contraction rate dC/dt = 3.h/1000 [mm/min]). The sealing or integrity capacity (E) is the element ability to keep the separation function, without transmitting the fire to the unexposed side, due to the passage of flames or hot gases. These may cause ignition of the unexposed surface or any material adjacent to that surface. The sealing assessment shall be carried out on the basis of the following three aspects: checking cracks or excessive opening of certain dimensions; existence of ignition of a cotton pad; existence of a permanent flame on the unexposed side. The insulation capability (I) is the ability of the element to withstand exposure to fire only on one side without significant heat transfer transmission from the exposed to the unexposed side. The transmission should be limited so that the unexposed surface or any material close to that surface is ignited. The classification (I) of a wall should be attributed based on the shortest time for which the criteria of maximum or average temperature increase are satisfied in any discrete area. The performance level used to define the insulation shall be calculated on the basis of the increase in average temperature on the unexposed side, limited to 140°C above the initial average temperature or based on the increase of maximum temperature, limited to 180°C above the initial average temperature.

According to EN 13501-2 [5], the protection given by a certain layer depends on the material backing this layer (cavity without insulation, second plate of gypsum, or cavity insulation material). To measure this effect, the protection given by a certain layer needs to be tested, using different backing materials, according with the testing method EN 14135 [9], assuming that for the classification period (10 min) there is no collapse of the covering and also that, during the test, the mean and the maximum temperatures measured on the unexposed side of the protection layer shall not exceed the initial temperature by more than 250 °C and 270 °C, respectively. This is the process used to find the protection given by a certain layer when backed by different conditions.

DESIGN METHOD USING THE SIMPLIFIED METHOD

The improved design method is based on the summation effect of each layer (cladding and cavity) and gives the fire resistance due to the insulation ability of the assembly. The total insulation time is based on the most critical heat flow pattern (any position between wood studs), being calculated by Eq. (1).

$$t_{ins} = \sum_{i=1}^{i=n-1} t_{prot,i} + t_{ins,n} \tag{1}$$

The first summation gives the protection time $t_{prot,i}$ (min) of the layers preceding the last layer of the assembly, see Figure 1. The insulation time due to the last layer is given in (min) by $t_{ins,n}$. The total insulation time is t_{ins} .

The protection time for the layers preceding the last one should be calculated using their basic values, the coefficients for their positions, the coefficients for the joints and the correction times, according to Eq. (2).

$$t_{prot,i} = (t_{prot,0,i} \times k_{pos,\exp,i} \times k_{pos,un\exp,i} + \Delta t_i) \times k_{j,i} \tag{2}$$

The protection time for the last layer should be given by Eq. (3), considering the basic insulation time, the coefficient for its position, the correction time and the coefficient for the joints.

$$t_{ins,n} = (t_{ins,0,n} \times k_{pos,\exp,n} + \Delta t_n) \times k_{j,n} \tag{3}$$

For all the proposed factors, the next tables should be applied. The basic values correspond to the fire resistance of a single layer, without the influence of adjacent materials (see Table 1).

Table 1 - Basic values for protection layers and insulation layer [7], h_i (mm)

Material	Basic insulation $t_{ins,0,n}$ min	Basic protection $t_{prot,0,i}$ min
Gypsum	$24 \times (h_i / 15)^{1.4}$	$30 \times (h_i / 15)^{1.2}$

The position coefficient for layer "i" may be defined as the ratio between the contribution to the fire resistance of the layer $t_{prot,i}$, with respect to its basic protection $t_{prot,0,i}$. The influence of the layers preceding and backing the layer under analysis "i" is included by the coefficient $k_{pos,\exp,i}$ and $k_{pos,un\exp,i}$.

The contribution to the fire resistance of the layer "i+1" is usually smaller that the contribution of the layer "i" due to the fact that previous protection layers are falling off exposing the current protection layer to higher temperature level, which means that is submitted to a different boundary condition when compared to the previous ones.

The coefficients for position were calculated by Frangi *et al.* [7], assuming that the layers fell off when the temperature on the unexposed side of each layer protecting layer increased by 250 ºC above the initial average temperature, see Table 2 and Table 3. This assumption is assumed by the same authors as conservative.

Table 2 - Coefficients for position affecting the exposed protection layers and exposed insulation layer [7]

Material	$k_{pos,\exp,n}$ for insulation	$k_{pos,\exp,i}$ for protection
Cladding (Gypsum, timber)	$1-0.6\times\frac{\sum t_{prot,n-1}}{t_{ins,0,n}}$ if $\sum t_{prot,n-1}\le\frac{t_{ins,0,n}}{2}$ $0.5\times\sqrt{\frac{t_{ins,0,n}}{\sum t_{prot,n-1}}}$ if $\sum t_{prot,n-1}>\frac{t_{ins,0,n}}{2}$	$1-0.6\times\frac{\sum t_{prot,i-1}}{t_{prot,0,i}}$ if $\sum t_{prot,i-1}\le\frac{t_{prot,0,i}}{2}$ $0.5\times\sqrt{\frac{t_{prot,0,i}}{\sum t_{prot,i-1}}}$ if $\sum t_{prot,i-1}>\frac{t_{prot,0,i}}{2}$

Based on the experimental results and numerical simulation, Frangi *et al.* [7], showed that the influence of the layer backing the layer under consideration "i" is small, if the backing layer is made of gypsum or wood, which explains the value 1.0. The influence of an insulation material, backing the layer under consideration "i" is important, because the temperature of that layer increases faster.

Table 3 - Coefficients for position affecting the unexposed side of the protection layers [7], hi (mm)

Material	$k_{pos,un\exp,i}$ for layers backed by cladding made of gypsum and timber	$k_{pos,un\exp,i}$ for layers backed by insulation material in the cavity
Cladding (Gypsum)	1.0	$0.5\times(h_i)^{0.15}$

The effect of the cavity without insulation material is considered by a modification of the coefficients for position of each layer in contact with the cavity, see Table 4.

Table 4 - Modified coefficients for position affecting the protection layers and insulation layer due to the existence of void cavity [7]

Material	Layer on the exposed side	Layer on the unexposed side
Cladding (Gypsum, timber)	$k_{pos,un\exp,i}$ see Table 3, column 3	$1.6\times k_{pos,\exp,i}$ see Table 2 $3\times\Delta t_i$ or $3\times\Delta t_n$ see Table 5

The correction times are presented in Table 5, to compensate the assumed conservative approach. These correction times were calculated by finite element simulations, using a temperature criterion of 600 ºC for the boards falling off, see Table 5. This correction times should only be used in case of layers protected (preceded) by type F gypsum plasterboards and gypsum fibre boards.

Table 5 - Correction times used for protection and insulation [7]

Material	Δt_n for $t_{ins,n}$ (min)	Δt_i for $t_{prot,i}$ (min)
Cladding (Gypsum, timber)	$0.03\times t_{prot,n-1}+0.9\times t_{ins,0,n}-2.3$, $t_{ins,0,n}<12\,\text{min}$	$0.03\times t_{prot,i-1}+0.9\times t_{prot,0,n}-2.3$, $t_{prot,0,i}<12\,\text{min}$
	$0.22\times t_{prot,n-1}-0.1\times t_{ins,0,n}+4.7$, $t_{ins,0,n}\geq 12\,\text{min}$	$0.22\times t_{prot,i-1}-0.1\times t_{prot,0,i}+4.7$, $t_{prot,0,i}\geq 12\,\text{min}$

The coefficients that accounts for the effect of the joints are not included in this investigation, because all the simulations were assumed without joints. The existence of joints are allowed up to the limiting value of 2 mm, according to EN1995-1-2 [6]. For simplicity, this design method considers the influence of joints in the insulation layer and for the layer preceding a void cavity. For all the other layers, the unit value should be considered.

NUMERICAL MODEL

The numerical model considers one cross section of the assembly, using perfect contact between all the materials, see Figure 2. The boundary conditions are applied in the exposed and unexposed sides, according to EN1991-1-2 [13]. The applied conditions are radiation with a fire emissivity value of 1 and convection with a coefficient of 25 W/m^{2}K on the fire side using the ISO834 [2] for bulk temperature and convection on the unexposed side with a convection coefficient equal to 9 W/m^{2}K and bulk temperature equal to 20ºC. An extra boundary condition is applied in the cavity region to account for the main events of cracks and falling off, that usually occur during the experimental tests. This extra boundary condition is applied in the internal region of the cavity and represents these events during all the simulation process. For this reason, an intermediate convection coefficient is applied, 17.5 W/m^{2}K, with an extra boundary condition for radiation, using the bulk temperature, previously defined by experimental tests (temperature in the cavity region). These temperatures in the cavity region were determined by standard experimental tests developed on LSF walls (specimen 8, [11] and specimen 11, [12]) with similar walls, using specimens with similar dimensions and number of studs. Authors believe that these main events are similar when using light steel frames and timber frames.

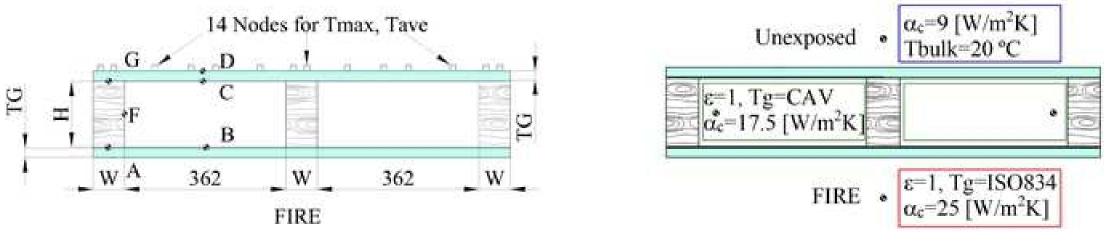


Fig. 2 - Geometric model and boundary conditions

The numerical model is used to solve the transient non-linear thermal analysis, considered by non-linear behaviour of the materials and the incremental solution process, based on a variable time step (1 s to 60 s). The non-linear convergence criterion is based on the heat flow, considering a tolerance value of 0.001 and a reference value of 1.0E-6.

Figure 3 represents the material properties used for wood and gypsum material. The amount of moisture in both materials is responsible for the peak values used for the specific heat.

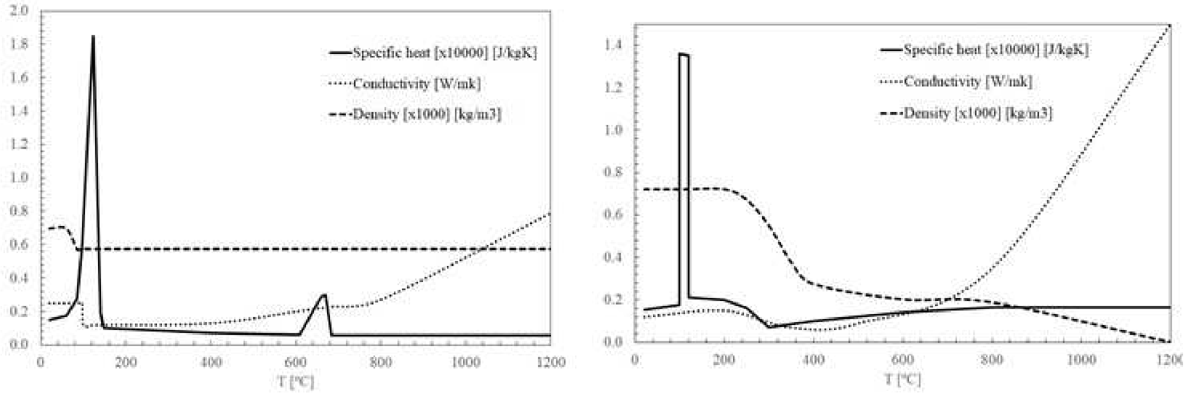
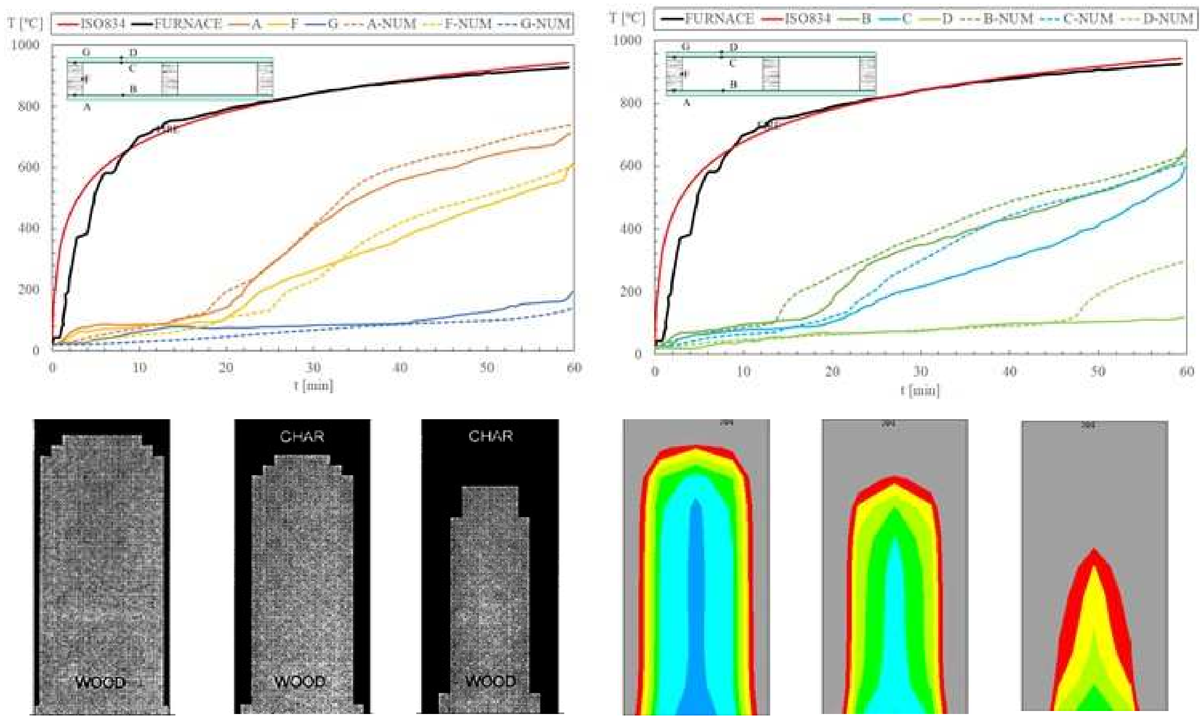


Fig. 3 - Material properties for gypsum and wood

The quadrilateral PLANE55 finite element is used with 4 nodes and 2 degrees of freedom in each node. This element uses linear interpolating functions and full integration gauss method.

The model was validated using the experimental test, specimen 6, developed by Takeda and Mehaffey [10]. The geometry of this model used H=89 mm and W=38 mm, lined with one gypsum plate of 16 mm. The model was validated for the time-temperature history on specific points that are identified in Figure 2, see Figure 4. The model was also validated to find the residual cross section of the studs, after being fire exposed to 40, 50 and 60 minutes. The furnace temperature was modelled according to the stepping Furnace curve.



40 min 50 min 60 min 40 min 50 min 60 min

Fig. 4 - Comparison for the temperature evolution at specific points and residual stud area

This numerical model is prepared to give results for the fire resistance (Insulation) for this light timber wall using different values for the protection layers (gypsum plates) and the residual cross section, for different wood studs. The results are being presented in the next section, using a parametric analysis.

PARAMETRIC ANALYSIS

The parametric analysis was developed to verify the effect of the size of the solid wood stud, which is responsible to modify the thickness of the cavity region, and also to verify the effect of the number of protection layers (gypsum fireboards). Table 6 presents the main results of the 24 simulations, using 6 different cross sections for wood studs (H – height and W- width) and 4 different levels of protection layers (TG). These results include the fire resistance (t_{ins}), when considering the criterion for the maximum temperature T_{max} and average temperature T_{ave}, finding the time to reach an increase of 180 ºC or 140 ºC above the initial temperature of the nodes (20 ºC), respectively, see Figure 5.

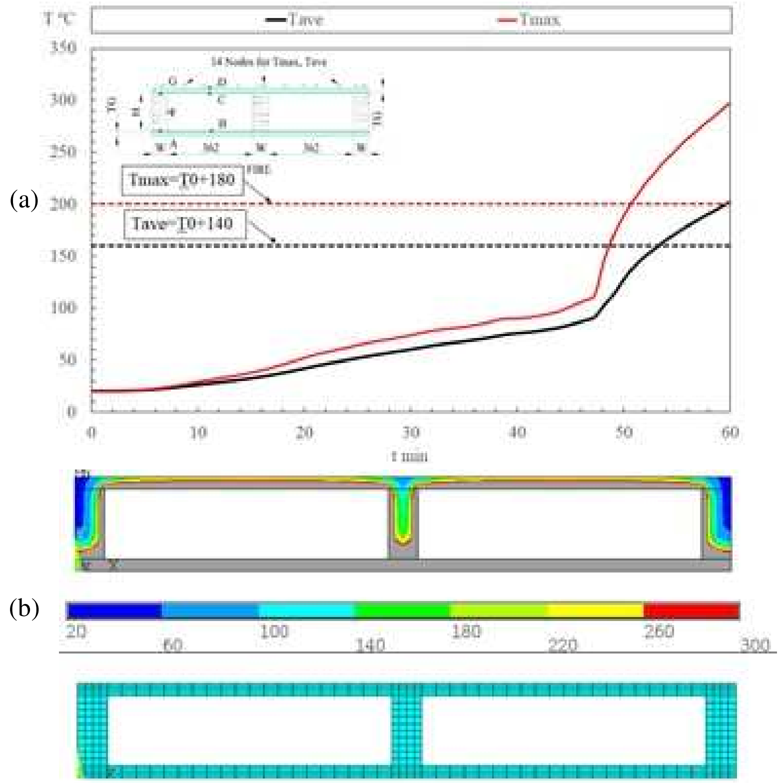


Fig. 5 - Thermal performance of the specimen [89x38]+16x1: (a) Time-temperature history for the unexposed side; (b) Finite element mesh and temperature for 50 minutes

Table 6 also presents the results for the residual area of the stud, after the wall being exposed to 40, 50, 60, 70, 80 and 90 min. The simulations using one protection layer for the timber structure ran for 60 minutes and allowed for the calculation of the residual area for time equal to 40, 50 and 60 minutes. The simulations using two protection layers ran for 120 minutes and allowed for the calculation of the residual area between 40 and 90 minutes.

The numerical results are presented for the fire resistance (t_{ins}), using both criteria, the maximum (T_{max}) and the average temperature (T_{ave}). These values are determined from the nodal data collected in the unexposed side, using 14 nodes, see Figure 2 and Figure 5. The fire resistance used for the insulation performance considered the average criterion ($T_{ave)}$ for comparison with the results determined using the simplified method. It looks that the simplified method is over predicting the results when using one protection layer and under predicting the results when using two protection layers, see Figure 6.

Table 6 - The fire resistance of the Light timber frame walls and the residual area of the central stud

[HxW]+TG	AREA [mm^2]	t_{ins} (num) Tmax [min]	t_{ins} (num) Tave [min]	t_{ins} (Sim. model) [min]	R40 [%]	R50 [%]	R60 [%]	R70 [%]	R80 [%]	R90 [%]
[89x38]+16x1	3382	50	53	68	70.8%	52.3%	24.4%	-	-	-
[115x38]+16x1	4370	51	53	68	75.1%	56.7%	29.3%	-	-	-
[140x38]+16x1	5320	52	54	68	75.7%	58.3%	34.3%	-	-	-
[89x38]+12.5x1	3382	41	43	53	64.7%	46.0%	14.8%	-	-	-
[115x38]+12.5x1	4370	41	43	53	69.2%	51.7%	18.4%	-	-	-
[140x38]+12.5x1	5320	42	44	53	70.7%	53.9%	21.8%			
[89x45]+16x1	4005	51	53	68	71.9%	56.5%	41.3%	-	-	-
[115x45]+16x1	5175	51	54	68	75.6%	60.7%	47.2%	-	-	-
[140x45]+16x1	6300	52	54	68	74.4%	62.7%	49.7%	-	-	-
[89x45]+12.5x1	4005	41	43	53	66.7%	51.6%	36.0%	-	-	-
[115x45]+12.5x1	5175	42	44	53	70.7%	56.4%	42.6%	-	-	-
[140x45]+12.5x1	6300	42	44	53	72.4%	58.4%	45.6%	-	-	-
[89x38]+16x2	3382	120	122	109	100.0%	100.0%	99.5%	92.5%	67.4%	44.2%
[115x38]+16x2	4370	120	122	109	100.0%	100.0%	100.0%	94.8%	72.1%	49.3%
[140x38]+16x2	5320	121	123	109	100.0%	100.0%	99.6%	95.7%	73.2%	51.9%
[89x38]+12.5x2	3382	107	106	87	100.0%	98.4%	93.4%	86.7%	58.6%	34.1%
[115x38]+12.5x2	4370	107	106	87	100.0%	99.0%	95.4%	90.2%	64.4%	41.0%
[140x38]+12.5x2	5320	107	108	87	100.0%	99.0%	96.1%	91.8%	66.5%	44.6%
[89x45]+16x2	4005	120	122	109	100.0%	100.0%	100.0%	92.8%	70.5%	52.2%
[115x45]+16x2	5175	120	123	109	100.0%	100.0%	99.9%	94.7%	74.4%	56.7%
[140x45]+16x2	6300	121	123	109	100.0%	100.0%	99.9%	95.9%	76.0%	58.5%
[89x45]+12.5x2	4005	106	107	87	100.0%	98.3%	93.3%	87.1%	61.9%	44.9%
[115x45]+12.5x2	5175	106	108	87	100.0%	98.7%	95.2%	90.5%	67.1%	50.7%
[140x45]+12.5x2	6300	107	108	87	100.0%	99.1%	96.2%	92.3%	69.6%	53.4%

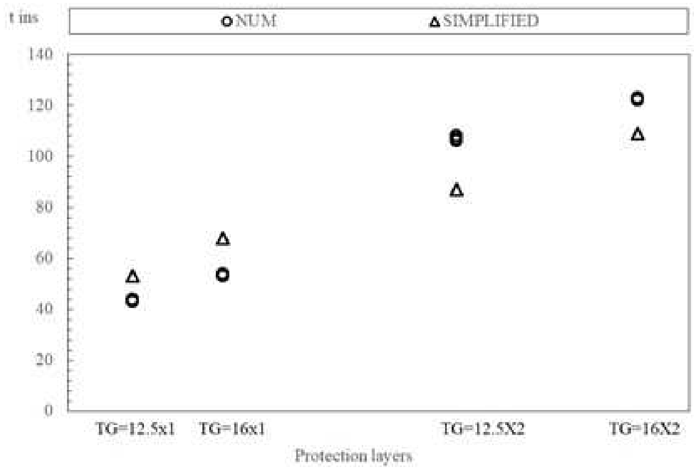
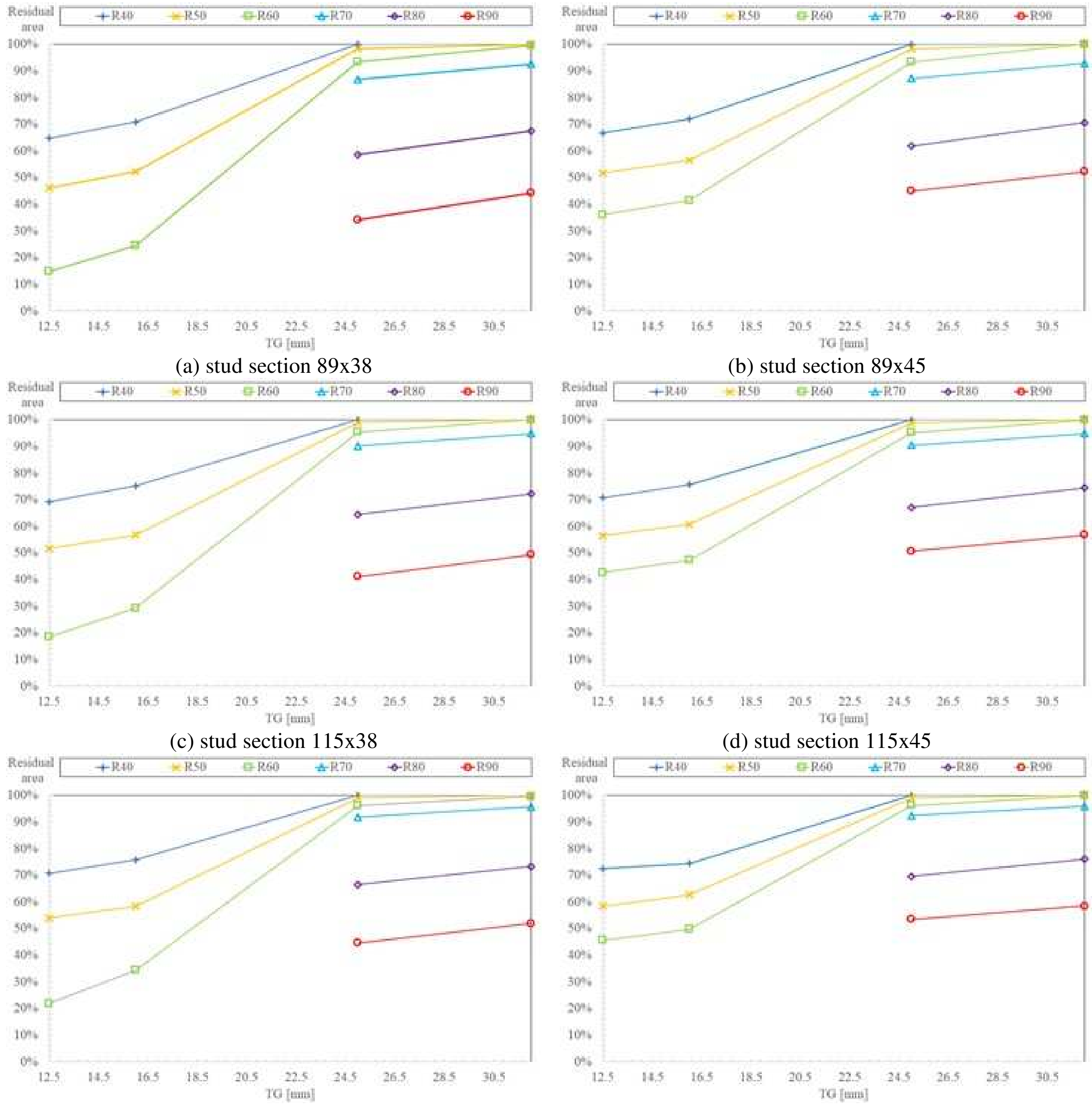


Fig. 6 - Fire resistance for insulation performance. Comparison between numerical and simplified methods

The residual area depends on the size of the wood stud and on the level of protection (TG). This fact is very important for the calculation of the residual load bearing of any fire affected light timber framed wall. The increasing of the size dimension W by 18.4% produces a great increase on R60 when using a single protection layer, and a moderate increase on R90 when using a double protection layer, see Figure 7.



(a) stud section 89x38

(b) stud section 89x45

(c) stud section 115x38

(d) stud section 115x45

(e) stud section 140x38

(f) stud section 140x45

Fig. 7 - Residual area for different time periods

CONCLUSIONS

This investigation presented a numerical model to predict the fire resistance due to insulation effect and the residual area of the wood stud, of light timber framed walls, lined with gypsum layer plates. The numerical model was validated with experimental results and a parametric analysis has been developed to evaluate the effect of the protection level (layers of gypsum plates, TG) and the effect of the area of the wood stud.

According to the results, the dimension increase of the wood stud does not provide almost any modification to the fire resistance by insulation. The maximum variation in the fire resistance was found to be 1 minute, when increasing the area by 57%.

The increase of the wood stud provides an increase on the residual area, especially for R60, when protected by single layer of gypsum plates. For single layer protection with 12.5 mm thick, the increase can be higher than 100%. The increase of the residual area for R90, when protected by double layer of gypsum plates is approximately equal to 20% for double layer protection using 2x12.5 mm and 15% for double layer protection using 2x16 mm.

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