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LOAD BEARING CAPACITY OF FIRE RATED LIGHT TIMBER FRAME WALLS

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Abstract Light timer frame (LTF) walls are made of solid timber elements (studs and tracks) and are usually protected by fire insulation materials (gypsum). This investigation finds the residual load bearing capacity of LTF walls after certain fire rating periods (30, 60, 90 and 120). One LTF structure with 3 studs will be analysed with two different protection levels (one and two gypsum layers). The computational model includes the thermal analysis under standard fire and a sequential mechanical analysis with incremental load applied for each fire rated periods. The orthotropic material behaviour is considered temperature dependent, the mechanical analysis considers large displacement behaviour and the charring effect of wood. The results show that the load bearing capacity decreases with the fire exposure time. A new proposal is presented between the load bearing capacity and the fire rating.

1. INTRODUCTION

Light timber framed walls are made with solid wood members (studs and tracks) used on buildings, for load bearing and partition walls. The assemblies are made with solid stud wood vertical members, each separated by 400 to 600 mm. The cladding for internal walls may be developed by wood panels, composite panels and or gypsum panels. The number of protection layers and insulation materials used in the cavities of the wall depends on the thermal and acoustic efficiency required to the TFW at room temperature, but also depends on the fire rating of TFW required. Wood has been widely used in building due to its good environmental impact. However, timber structures are highly vulnerable to fire because of its combustion process.

For the case of load bearing walls, the vertical load is transmitted through the studs and panels may increase the stability of the vertical elements, depending on the stiffness of the connection between the panels and the studs. Panels may be also supporting orthogonal and in plane loads, in case of external walls submitted to wind loads and seismic loads. The fire resistance should be verified for the load bearing capacity (R), insulation (I) and integrity (E), usually using experimental standard tests, specimen instrumentation and criteria defined on EN1363-1 [1], EN1365-1 [2], ISO834 [3].

For the case of non-load bearing walls, the fire resistance should be verified for the insulation (I) and integrity (E), usually using the same type of procedures EN1363-1 [1], EN1364-1 [4] ISO834 [3].

Load bearing and Partition wall systems used in residential and commercial properties are required to provide fire rating according to times established in the fire classification of construction products and building elements, EN13501-2 [5]. Partition walls can be rated for EI=15, 20, 30, 45, 60, 90, 120, 180 and 240 min, while the load bearing elements can be rated for REI=15, 20, 30, 45, 60, 90, 120, 180, 240 and 360 min. The safety level is then selected by each European country, using its own national regulation system.

During the last years, only a few experimental tests have been carried out. In 1998, Takeda and Mehaffey [6] developed some experimental tests, that have already been validated, using 2D numerical models using Ansys [7]. In 2010, Thomas [8] tested the suitability of the finite element heat transfer program SAFIR for modelling plasterboard-lined LTF assemblies. Similar results were obtained with the program TASEF with slight differences. Both programs seem to give better overall results for slower developing fires and furnace tests than more rapidly growing fires. This research also concludes that more sophisticated models, including mass transfer, effect of connections, gaps between panels and ablation are required to achieve better comparisons. In 2018, Thi et al. [9] studied the behaviour of cross-laminated timber (CLT) panel in the central part of the wall system, where the pyrolysis of timber was modelled explicitly in the energy equation, implementing a user subroutine called UMATHT, in Abaqus for thermal analysis. The falling off of the gypsum boards under fire was considered implicitly in the FE model based on experimental observations. Results show the need to consider explicitly the cracks and falling off of the gypsum boards for an appropriate prediction of the integrity fire resistance. In 2019 Chiara Bedon and Massimo Fragiacomo developed an experimental and finite element study to evaluate the fire behaviour of unprotected log-haus timber walls in fire conditions under in-plane compressive loads. Numerical results were

validated and a parametric analysis was performed, considering the most important parameters. The effects of these parameters are presented in terms of overall buckling resistance and failure modes, providing evidence for the reduction the load bearing capacity. In 2020 Fonseca et al. [10] determined the fire resistance of unprotected wood connections and evaluated the efficiency of the protection using gypsum plasterboard. In 2021 Qin et al. [11] made experimental tests to evaluate the fire behaviour of wood components under different service loads. Authors concluded that service load can accelerate the charring rate and increase the charring depth, proposing a new formula to determine the charring rate, depending on the service load.
This numerical investigation deals with two different levels of fire protection applied to TFW, evaluating the load bearing capacity for different fire rated times. The simulations are based on a two-step simulation process, submitting the TFW under the thermal effect of the fire, using two experimental fire scenarios used for LSF walls developed by Piloto et al. [12] and Khetata et al. [13] (single layer protection during 60 minutes and double layer protection during 120 minutes) and then for each fire rated time a thermomechanical analysis is developed to determine the load bearing capacity. For the first fire scenario, the load bearing capacity is determined for R30 and R60, while for the second fire scenario, the load bearing capacity may be determined for R30, R60, R90 and R120.

2. MATERIALS AND METHODS

The TFW assemblies under evaluation are made with 3 solid timber elements used for studs and 2 solid timber elements as tracks, each with a cross section of 100x50 mm. The dimensions are defined according to the furnace dimensions, see Fig. 1.

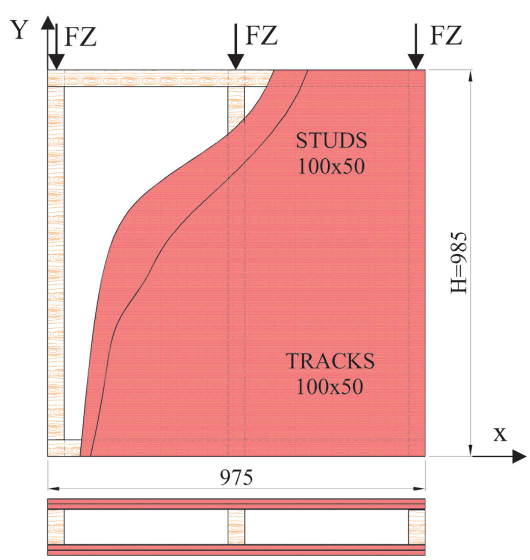


Figure 1. Timber Frame Wall.

The specimens are tested according to Table 1. The fire scenario inside the cavity includes the effect of the falling off during experimental tests. This damage effect has been considered by an additional boundary condition inside the cavity due to radiation and convection.

Specimen	Protection layers Gypsum	Fire scenario exposed surface	Fire scenario inside cavity
01	1x12.5 mm	ISO 834 [3]	FIRE CAVITY 01 Specimen 08 [12]
02	2x12.5 mm	ISO 834 [3]	FIRE CAVITY 02 Specimen 11 [13]

Table 1. Specimens used for the numerical simulation of TFW.

The fire scenarios are depicted in Figure 2 and they consider different fire durations. The fire cavity 01 is typically used for 1 hour of standard fire, being the temperature in the cavity region define by this curve. The fire cavity 02 consider a standard fire event of 2 hours and the temperature in the cavity follows this curve. Both curves are compared with the same standard fire used for the exposed surface. The main difference between fire cavity 01 and 02 is related with the insulation level of the cavity region. The cavity 01 will be exposed to fire after 19 min, while the other cavity 02 is going to be exposed after 41 min.

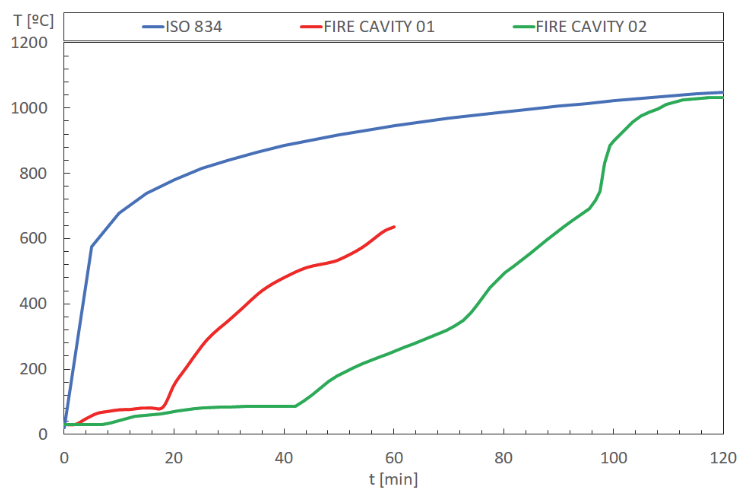


Figure 2. Fire curves used for Timber Frame Walls.

2.1. Material properties

The material properties involved in these simulations are the thermal properties for wood and gypsum (conductivity, specific heat density and emissivity) and the mechanical properties for wood members (elastic, plastic and damage criterion).
The thermal properties for both materials involved are presented in Figure 3 and Figure 4

and they are based on the EN1995-1.2 [14] and based on Sultan investigation [15].

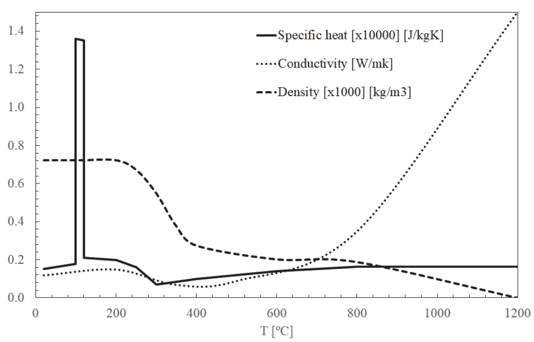


Figure 3. Thermal properties for wood.

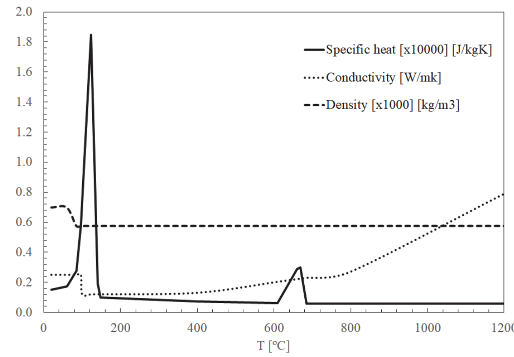


Figure 4. Thermal properties for gypsum.

The emissivity of both materials are considered to be 0.8 [14], [15].

The mechanical properties are only presented for the material that is capable to bear the vertical load. Wood is a highly anisotropic material, due to the manner in which a tree grows and the arrangement of the wood cells within the stem. Wood can be considered locally as an orthotropic material that possesses three principal directions. The pine wood model considers different behaviour of the material in the direction of the fibres, radial direction and tangential direction. The strength and stiffness of wood are considerably higher in the longitudinal than in the orthogonal directions. This can be easily understood on the basis of 90±95% of the fibres are longitudinally oriented [16]. The generalized Hooke law for an orthotropic material is considered.

Moreover, According to EN1995-1.2 [14] it is possible to conclude that the strength for wood in the direction parallel to the grain is linearly reduced with increasing temperature, more accentuated up to 100 ° C. The modulus of elasticity is also affected by the increase in temperature. The reduction factors were used for 100 and 300 ºC. Poisson's coefficients are considered constant in the face of temperature rise, because Eurocode 1995-1-2 [14] does not define correction factors to be applied for this property. The transverse elastic modulus also undergoes a reduction with increasing temperature, and the same reduction coefficients of the modulus of elasticity are used, since both elastic properties of wood are related through Poisson's coefficients.

The rupture can present itself in several ways, such as fibre breakage, micro-cracking of the matrix, detachment of fibres or delamination. To characterize this effect, the Hill criterion is adopted. This criterion is based on von Mises's theory and adapted for application in anisotropic materials. Hill's criterion considers the interaction between the stresses in the failure mechanism, and depends on the orientation of the stress in relation to the anisotropy axis of the material. This criterion allows the determination of the elastic and elastoplastic zones in the tension-deformation relationship of the wood. The characteristic parameters of the anisotropy of the material, determined for the criterion are the Rij yield rates, established as a function of the limit stresses in the main directions of the material. knowing that the

wood does not have plastic capacity and knowing that the perfectly elastic plastic regime is considered in the model of this study just to ensure that the material has an elastic limit. The tensile strength f_{xx}^{y} value is 44.49, 28.92 and 0.44 MPa, for each temperature level (20, 100 and 300 ºC).
Table 2 gives the values used for the elastic behaviour of the material, while Table 3 gives the yielding rates used for each orthogonal direction and temperature level.

	Temperature		
	20	100	300
EX [N/m2]	$1.12\text{x}10^{10}$	$5.60\text{x}10^{09}$	$1.12\text{x}10^{08}$
EY [N/m2]	$4.48\text{x}10^{08}$	2.24x1008	$4.48\text{x}10^{06}$
EZ [N/m2]	$9.86\text{x}10^{08}$	4.93x1008	$9.86\text{x}10^{06}$
μXY	0.315	0.315	0.315
μYZ	0.308	0.308	0.308
μXY	0.347	0.347	0.347
GXY [N/m2]	$9.07\ \text{x}10^{08}$	$4.54\text{x}10^{08}$	$9.07\text{x}10^{06}$
GYZ [N/m2]	$1.23\ \text{x}10^{08}$	$6.16\text{x}10^{07}$	$1.23\text{x}10^{06}$
GXZ [N/m2]	$1.08\ \text{x}10^{09}$	$5.38\text{x}10^{08}$	$1.08\text{x}10^{07}$

Table 2. Elastic material properties for wood.

	Temperature		
	20	100	300
RXX f_{xx}^{y}/f^{y}	1	1	1
RYY f_{yy}^{y}/f^{y}	0.052	0.052	0.052
RZZ f_{zz}^{y}/f^{y}	0.052	0.052	0.052
RXY $f_{xy}^{y}/\left(f^{y}/\sqrt{3}\right)$	0.405	0.405	0.179
RYZ $f_{yz}^{y}/\left(f^{y}/\sqrt{3}\right)$	0.405	0.405	0.179
RXY $f_{xz}^{y}/\left(f^{y}/\sqrt{3}\right)$	0.405	0.405	0.179

Table 3. Yielding rates for wood.

2.2. Finite element model for thermal analysis

The finite element model considers the different elements for the thermal analysis and for the mechanical analysis. For the thermal analysis, only the hexahedron SOLID70 is used. This element has eight nodes, each with one degree of freedom (temperature), uses linear interpolating functions and full Gauss integration 2x2x2.
The mesh is defined in Figure 5, for both specimens. The number of elements was obtained through a convergence test.
The solution method is considered incremental and iterative, due to the non-linearities involved in the materials properties and boundary conditions. The time step was selected to be 60s, but can be reduced to 1s. The criterion used for convergence is based on the heat

flow, using a tolerance value of 1% and a reference value of 10^{-6}.
Regarding standard fire exposure, the EN 1991-1-2 [17] establishes that for the exposed side of a construction element, the convection coefficient α_c=25 [W/m²K] should be used for ISO 834 standard fire exposure, whilst for the unexposed side the total heat transfer coefficient, α_c, equals 9.0 [W/m²K] when assuming the effects of combined radiation and convection. Additionally, emissivity of the flames is considered ε_f=1.0. For the TFW the initial temperature is constant and equal to T_0=20 °C applied to all nodes of the model.

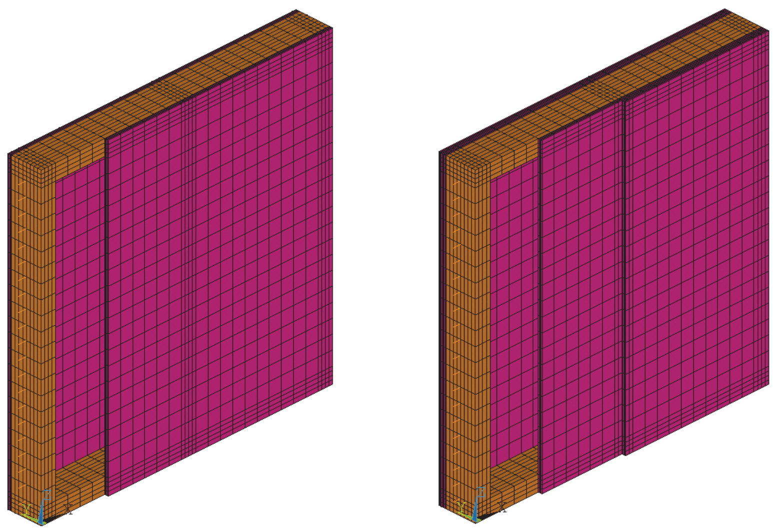
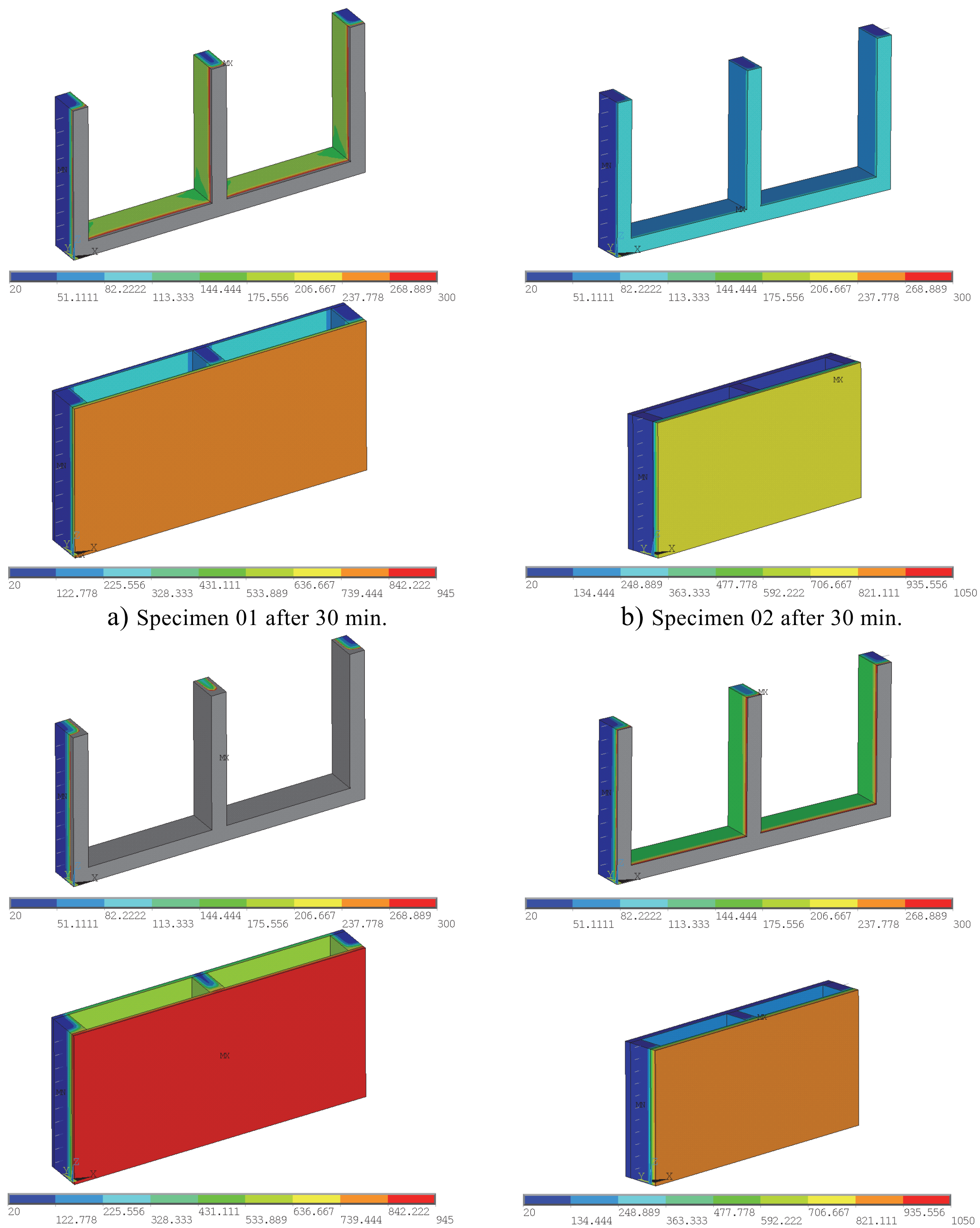


Figure 5. Fire element mesh for both specimens.

Based on previous numerical research [13], additional boundary condition is applied to all the internal surfaces of the cavity. The convection coefficient is set to α_c=17 [W/m²K] and the emissivity of the flames is ε_f=1.0, assuming that the bulk temperature of the cavity is following the fire cavity curves define in Figure 2. The convection coefficient is an average value between the exposed and unexposed side. This value may be justified by the fact cavity is not directly exposed to fire during all fire test, because depends on the gypsum cracking and falling off.
Results are evaluated for every time step, but Figure 6 depicts the temperature field for both materials and the charred zone (grey) of the timber elements, after 30 and 60min of fire exposure. Specimen 02 has higher fire protection, which reduces the temperature in both materials for the same time being considered.



a) Specimen 01 after 30 min. b) Specimen 02 after 30 min.

c) Specimen 01 after 60 min. d) Specimen 02 after 60 min.

Figure 6. Temperature results after 30 and 60 minutes of fire exposure.

The average and the maximum temperature are also calculated in the unexposed surface to determine the fire resistance due to insulation. The criterion is based on the increase of 140 ºC or 180 ºC above the initial average temperature ($\overline{T}_0$=20ºC). Both results are presented in Table 4.

	Tmax	Tave
Specimen 01	44	46
Specimen 02	91	91

Table 4. Fire resistance for insulation.

2.3. Finite element model for mechanical analysis

For the mechanical analysis, the hexahedron SOLID185 is used. This element has eight nodes, each with three degrees of freedom (translations in each spatial direction UX, UY; UZ), uses linear interpolating functions and full Gauss integration 2x2x2, with enhanced strain calculation. This model also includes an interface element COMBIN39, used to model the restrain effect of the frame used in the furnace. According to the standard used for testing these elements, EN1365-1 [2], the width of the test specimen is less than the opening in the test frame, with a clearance between 25 mm to 50 mm from the vertical edges of the test specimen. This clearance only restrains the motion of the wall studs to the outside region, but should not offer any restrain in the opposite direction of the stud.
The load bearing is determined for this loading condition, but depends on the initial condition on the geometry and material (imperfections). Different deformed shape modes may be expected for the TFW structure. A global imperfection, based on the maximum out of straightness equal to H/300, is applied to the first instability mode to update the initial geometry. Using this initial geometry, the vertical load versus the contraction "C" of the structure has been determined at room temperature, see Figure 7.

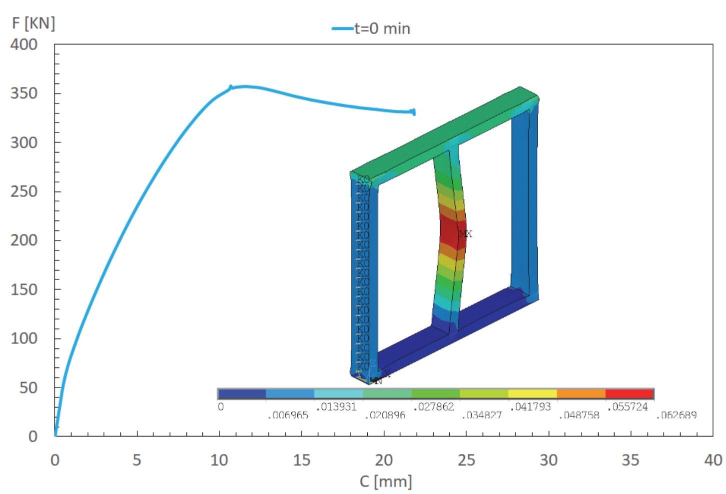


Figure 7. Load bearing capacity of the TFW.

The fire resistance has been determined after certain fire rating times, using the temperature field corresponding to this time and the same incremental and iterative procedure to determine the load bearing capacity.
These simulations use an incremental displacement applied on the top of the TFW structure, with a typical incremental displacement of 0.01 mm, that can change between 0.001to 1 mm, depending on the convergence process. The criterion used to achieve the convergence is based on the internal forces, using a tolerance of 5%. Figure 8 presents the reduction of the load bearing capacity for both specimens. The reduction has been determined based the measurement of the load for the same vertical contraction (C=2.2 mm), because different deformed shape modes are expected. These deformed shape modes depend on the charred layer of the timber frame and on the temperature field.

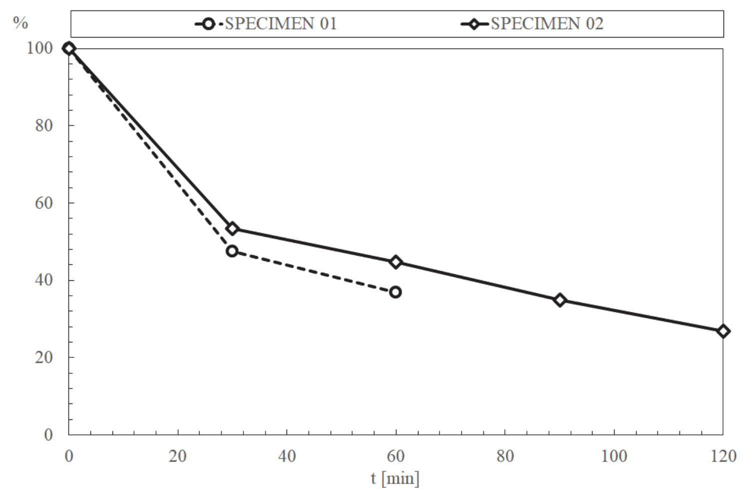


Figure 8. Load bearing reduction of the TFW.

The temperature field is affected by the level of protection given by the gypsum layers. Specimen 01 presents only one gypsum layer, which means that after 30 min, the load bearing capacity of this specimen is smaller than the load bearing of specimen 02 (using two protection layers of gypsum).
The same specimen can achieve different deformed shape modes for the ultimate state, see Figure 9, as an example for specimen 02, after 60 min and 120 min. The deformed shape mode for the central stud, after 120 min, presents an out of plane displacement towards the fire exposed side. This mode shape is explained by the amount of charred layer, being the most unexposed fibre responsible to sustain the residual compressive load. The in plane deformed mode shape may also be explained by the asymmetrical temperature field in the most external studs, due to the thermal protection of the specimen lateral edges, due to the contact with the furnace frame, see Figure 6.

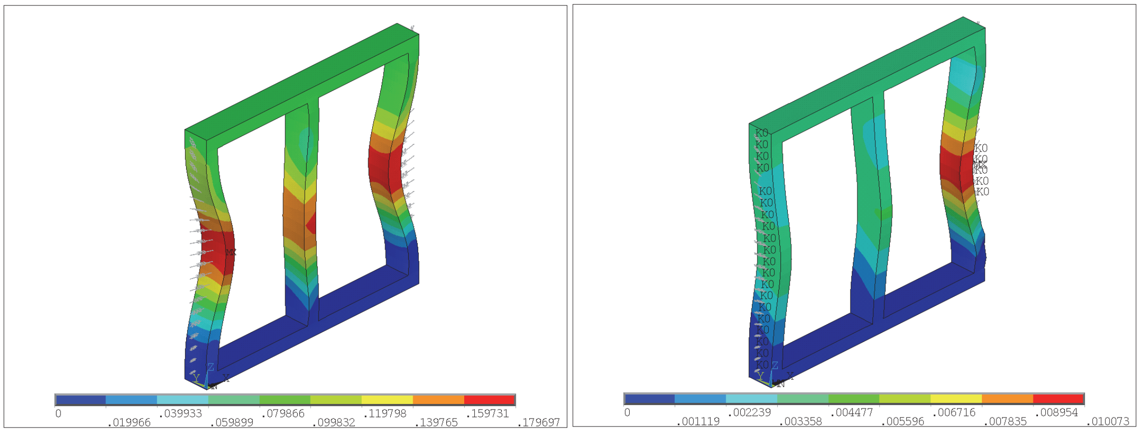


Figure 9. Deformed shape modes for TFW under the ultimate limit state.

3. CONCLUSIONS

This research presents the load bearing capacity of TFW protected with one and two layers of gypsum at room temperature and after different fire rating periods. The finite element model for the thermal analysis has already been validated, which demonstrates the ability to predict accurately the temperature field in the timber frame. Higher protection level reduces the charred layer of the studs and increases the load bearing capacity. The load bearing reduces with the increase of fire exposure time, as expected.

More simulations are expected to be developed based on different levels of protection layers, using different materials. Experimental tests are also required to validate the load bearing capacity.

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