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Fire safety engineering — Assessment, verification and validation of calculation methods —

Part 4:
Example of a structural model

Ingénierie de la sécurité incendie — Évaluation, vérification et validation des méthodes de calcul —

Partie 4: Exemple d'un modèle structural

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Foreword

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The committee responsible for this document is ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

ISO 16730 consists of the following parts, under the general title *Fire safety engineering — Assessment, verification and validation of calculation methods*:

— *Part 2: Example of a fire zone model* [Technical Report]

— *Part 3: Example of a CFD model* [Technical Report]

— *Part 4: Example of a structural model* [Technical Report]

— *Part 5: Example of an Egress model* [Technical Report]

The following parts are under preparation:

— *Part 1: General* (revision of ISO 16730:2008)

Introduction

Certain commercial entities, equipment, products, or materials are identified in this document in order to describe a procedure or concept adequately or to trace the history of the procedures and practices used. Such identification is not intended to imply recommendation, endorsement, or implication that the entities, products, materials, or equipment are necessarily the best available for the purpose. Nor does such identification imply a finding of fault or negligence by the International Standards Organization.

For the particular case of the example application of ISO 16730-1 described in this document, ISO takes no responsibility for the correctness of the code used or the validity of the verification or the validation statements for this example. By publishing the example, ISO does not endorse the use of the software or the model assumptions described therein and states that there are other calculation methods available.

Fire safety engineering — Assessment, verification and validation of calculation methods —

Part 4: Example of a structural model

1 Scope

This part of ISO 16730 shows how ISO 16730-1 is applied to a calculation method for a specific example. It demonstrates how technical and users' aspects of the method are properly described in order to enable the assessment of the method in view of verification and validation.

The example in this part of ISO 16730 describes the application of procedures given in ISO 16730-1 for a structural fire resistance model.

The main objective of the specific model treated here is the simulation of the heat transfer and structural responses of wall assemblies.

2 General information on the structural model

An analytical model for predicting the fire resistance of load bearing, gypsum protected, wood-stud wall assemblies is presented. The model couples a heat transfer sub-model and a structural sub-model. The heat transfer sub-model predicts the temperature profile inside the wood-stud wall and the time to insulation failure. The structural sub-model, based on the elastic buckling-load, uses the temperature profile to calculate the deflection of the wood studs and the time to structural failure of the assembly.

3 Methodology used in this Technical Report

For the calculation method considered, checks based on ISO 16730-1 and as outlined in this Technical Report are applied. This Technical Report lists in Annexes A and B the important issues to be checked in the left-hand column of a two-column table. The issues addressed are then described in detail, and it is shown how these were dealt with during the development of the calculation method in the right-hand column of the Annexes A and B cited above, where Annex A covers the description of the calculation method and Annex B covers the complete description of the assessment (verification and validation) of the particular calculation method. The Bibliography includes a worked example and user manual.

Annex A
(informative)

Description of the calculation method

A.1 Purpose

Definition of problem solved or function performed	To develop an analytical model to predict the fire resistance of lightweight wood-frame wall assemblies exposed to fires. The model evaluates the heat transfer and structural responses based on experimental observations, material properties at elevated temperatures and equations of strength of materials.
Description of results of calculation method	To simulate the fire resistance behaviour of wood-frame assemblies, it is essential to evaluate their thermal and structural responses when exposed to fires. The thermal response gives estimates of the temperature distribution in the assembly. The structural response calculates the structural failure of an assembly, based on this temperature distribution.
Inclusion of feasibility studies and justification statements	Traditionally, fire resistance of wood-frame assemblies has generally been evaluated by: — subjecting an assembly to testing in accordance with procedures outlined in standards or — using reference to ready-to-use tables or design procedures (component additive method) found in building codes or — alternatively, fire resistance can be evaluated using validated numerical models that are becoming available. Fire resistance test methods have drawbacks, including high costs and time, limitations of specimen geometry and loading, and to a lesser degree repeatability. Calculation methods offer one way of overcoming some of these problems when attempting to assess the fire resistance of lightweight-framed assemblies. Calculation methods also aid in designing an experimental program, improve products manufacturing, and assist the industry in taking full advantage of the opportunities offered by performance-based codes, as these methods would facilitate a faster design process.

A.2 Theory

Description of underlying conceptual model (governing phenomena), if applicable	In order to develop a fire resistance model for wall assemblies that replicate test results, the fire resistance behaviour from the experimental program must be carefully observed. Test results have shown that the behaviour of wood-stud wall assemblies, when exposed to fire, depends on several key factors: the layers of gypsum board separating the wood joists from the flames, the insulation between the joists, the material properties of the wood joists, and the temperatures to which the assembly is subjected. The model comprises two sub-models, a heat transfer sub-model and a structural response sub-model. The heat transfer sub-model, called WALL2D, predicts the thermal response. The heat transfer model determines the temperature distribution in the wall as a function of time, taking into account the heat absorbed in the dehydration of gypsum and wood, and in the pyrolysis of wood, without considering mass transfer. The heat transfer model uses thermo-physical properties of wood, gypsum board, and insulation. The heat transfer model also predicts the effect of glass-fibre and rock-fibre insulation on the fire resistance of wood-stud walls, by combining conduction and radiation heat transfer through the insulation, and is represented by a temperature-dependent effective thermal conductivity and density of the insulation. In addition, the heat transfer model calculates the flow of hot gases through the opening into the stud cavity based on shrinkage of gypsum board and opening of the joints, as well as the advance of the char layer into the cross-section of the stud with time. The structural fire performance of wood-frame assemblies is affected by the rate of charring, degradation of the mechanical properties of the wood at elevated temperatures, and the load sustained by the assemblies. To determine the structural response, a critical buckling sub-model is implemented with the heat transfer model. The sub-model uses the temperature distribution predicted by the heat transfer model as an input, then calculates the deflection and the critical elastic buckling-load for a wood-stud wall. The buckling of the wood studs is restricted to the strong axis because of the lateral support by the gypsum board. The stud's deflection is estimated using the theory of elasticity. The deflection of the stud, as predicted for a hinged-hinged eccentric column, can be calculated by considering the stud as a beam-column structure.

Description of theoretical basis of phenomena and physical laws on which calculation method is based, if applicable	The test results have shown also that by exposing a wood-frame wall to fire, the temperature in the gypsum board protection begins to increase first. After some time, the studs start to heat up, and then they char at temperature levels ranging between 280 °C and 300 °C. This causes the studs to deflect away from the fire. The deflection of the studs and the gypsum board increases gradually, leading to opening of the gypsum board joints. The gypsum board, attached to the studs, disables any lateral torsional buckling of the studs, so the wood stud deflects around its strong axis. As the opening increases, the wood studs become more exposed and the charring rate increases. For load-bearing wood walls, the heating and onset of charring of the stud create an eccentric load that can either be allowed to move or stay in place depending on the wall-end conditions (hinged vs. fixed conditions). As the cross-section area of the load-bearing studs starts diminishing (thickening of the charred area), the wall studs start experiencing excessive deflection and the load cannot be held by the studs any longer (buckling failure); this defines the structural failure of the wall. For non-load-bearing walls, assembly failure is governed mainly by excessive temperature rise on the unexposed side of the wall. The figure below shows the behaviour and failure mode of a wood-stud wall assembly. See Figure A.1.
	 **Figure A.1 —Behaviour and failure mode of wood-framed wall assembly**

A.3 Implementation of theory

Governing equations

The heat transfer, through gypsum boards and wood studs, is described using an enthalpy formulation, governed by the following equation:

$$\rho \frac{\partial H}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y} \right) \qquad (1)$$

where

ρ is the density (kg/m^3) ;

H is the enthalpy (J/kg) ;

t is the time (s) ;

k is the thermal conductivity (W/m °C) ;

T is the temperature (°C), and

x and y are the coordinates (m).

Formula (1) is solved using an explicit finite difference method.

The critical elastic buckling-load, assuming both ends of the studs are pinned, is given by:

$$P_{cr} = \frac{\pi^2 EI}{L^2} \qquad (2)$$

where

P_{cr} is the elastic buckling-load (N) ;

E is the modulus of elasticity of the resisting member (MPa) ;

I is the moment of inertia (mm^4), and

L is the actual stud length (mm).

The values of the moment of inertia and modulus of elasticity change with time. For the moment of inertia, the heat transfer model provides an estimation of the remaining cross-section of the stud. For the modulus of elasticity, the change with temperature is obtained from the literature.

The rigidity (product of the modulus of elasticity and the moment of inertia), for each stud in the wall and based on meshing the stud, is calculated as follows:

$$EI = \sum_{i}^{m} E_i \frac{b_i D_i^3}{12} + \sum_{i}^{m} (b_i D_i)(Y - y_i)^2 E_i \qquad (3)$$

where

b_i is the element width (mm) ;

D_i is the element depth (mm) ;

Y is the stud centroid (mm) ;

y_i is the element centroid (mm), and

E_i is the temperature dependent modulus of elasticity of the element (MPa).

The differential equation giving the deflection can be written as follows:

$$EIy'''' + Py'' = 0 \qquad (4)$$

where

y is the out-of-plane deflection (mm) ;

EI is the stud rigidity (N-mm^2), and

P is the applied load (N).

Governing equations
The deflection, y, at any height x on the stud at any time, as: $$y(x)=\frac{M_0 L^2}{8EI}\left[\frac{2\cos\left(\Psi-\frac{2\Psi}{L}x\right)-\cos(\Psi)}{\Psi^2\cos(\Psi)}\right]$$ (5)
With $\Psi=\frac{\pi}{2}\sqrt{\frac{P}{P_{cr}}}$ and $M_0=P(e_c-e_p)$
where
L is the length of the stud (mm) ;
e_c is the eccentricity of the centroid of the resisting member (mm), and
e_p is the applied load eccentricity (mm).

Governing equations
In addition to the deflection due to the loading, the eccentricity of the surface of the wood affects the deflection of the stud. In general, the eccentricity can be expressed with a sinusoidal equation:
$$y_e = e * \sin\left(\frac{\pi x}{L}\right) \quad (6)$$
where
y_e is the magnitude of the deflection due to eccentricity ;
e is the maximum eccentricity ;
x is the position along the stud, and
L is the length of the stud.
This value can be added to the eccentricity due loading to obtain the overall deflection as:
$$\Delta = y(x) + y_e \quad (7)$$

Mathematical techniques, procedures, and computational algorithms employed, with references to them	The sub-model assumes that heat transfer occurs mainly in the cross-section of the wall assembly and that heat flow in the vertical direction can be ignored. The finite difference mesh considers symmetry of the wall, with a mesh refinement in proximity of the wood stud and larger spacing within the gypsum board far from the wood stud.
Identification of each assumption embedded in the logic, taking into account limitations on the input parameters that are caused by the range of applicability of the calculation method	The model is based on one stud analysis and failure of the analysed stud means failure of the wall. The heat transfer model does not include the effect of moisture movement. The structural model is based on the elastic buckling analysis. The model predicts the fire resistance of wall exposed to standard fire. The model has not been checked for real fire exposures. The model is not capable of modelling the decay phase of a fire. The accuracy of the material properties at elevated temperatures is limited to one used in the model.
Discussion of precision of the results obtained by important algorithms, and, in the case of computer models, any dependence on particular computer capabilities	Based on the validation carried out, the predictions of the structural failure are generally accurate within 10 % of the measurements. More validation may be necessary to have a real range of accuracy. Currently the model can handle grid size of minimum 1,6 mm and the time step used in the analysis is 1 s.
Description of results of the sensitivity analyses	In order to determine the critical factors affecting the fire resistance model, a parametric study has been carried out using the model. For the parametric study, all wall assemblies consisted of 10 studs with a cross-section of 89 mm by 38 mm wide, 400 mm apart, held in place by nails. The parameters considered in the structural response included the modulus of elasticity, stud length and the applied load on the assembly. The parameters considered in the thermal response included the wood density, and the nail spacing. All these parameters have had an impact on the time to failure of the assembly.

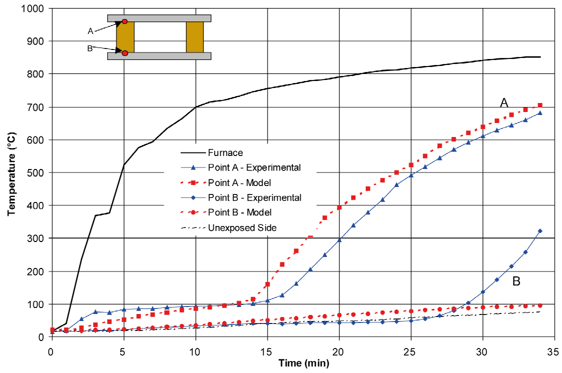
A.4 Input

Description of required input	The input data are done though a graphical user's interface (see user's manual for more details): — type of wood species ; — geometry of the stud (cross section and length) ; — charring temperature ; — load applied and number of studs ; — mechanical properties at ambient temperature ; — number of layers, type, and thickness of the gypsum board on both sides of the wall assembly ; — type and density of the insulation ; — nail spacing.
Information on the source of the data required	Geometry and construction details are input by the users. Material properties at elevated temperatures from tests and literature.
For computer models: any auxiliary programs or external data files required	No.
Provide information on the source, contents and use of data libraries for computer models	None needed from external sources.

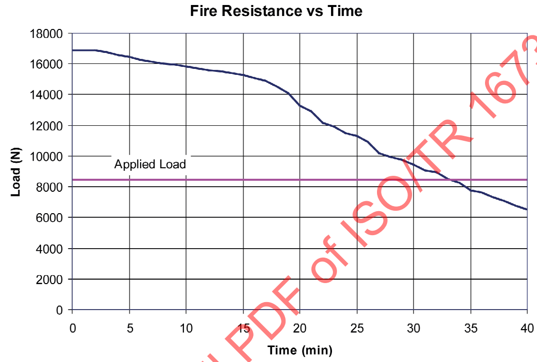
Annex B
(informative)

Complete description of the assessment (verification and validation) of the calculation method

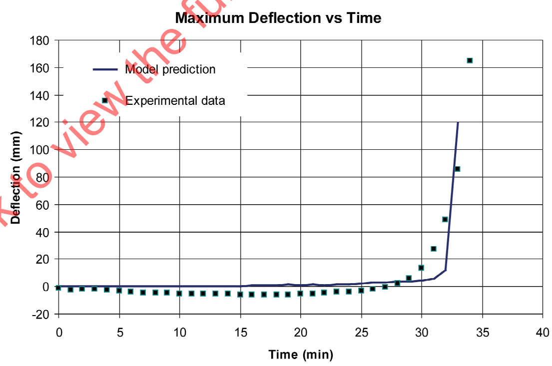
Results of any efforts to evaluate predictive capabilities of calculation method in accordance with ISO 16730-1	In order to verify the validity of the model, it is necessary to compare the predictions with experimental data. Tests were used to evaluate the predictions by the fire resistance model. The assemblies contained glass fibre in the cavity.
To be presented in a quantitative manner	The predictions of time-temperature curves generated by the heat transfer have been used to calculate the reduction in load-carrying capacity of the studs and the degradation in the modulus of elasticity. Temperatures on the unexposed sides did not reach the insulation failure criterion, as the two assemblies failed by structural instability at 34 and 41 min for tests a) and b), respectively (see below graphs).



Temperature (°C)
Time (min)
A
B
Furnace
Point A - Experimental
Point A - Model
Point B - Experimental
Point B - Model
Unexposed Side

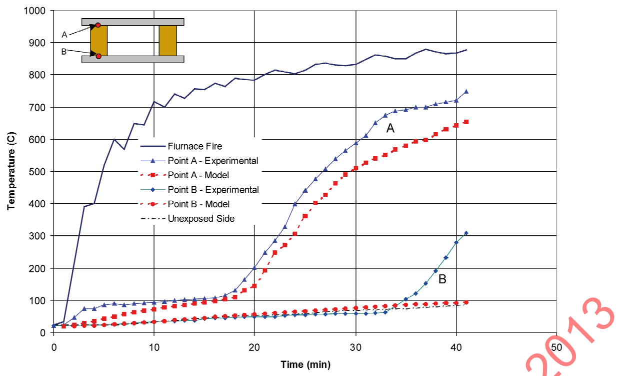


Fire Resistance vs Time
Load (N)
Applied Load
Time (min)

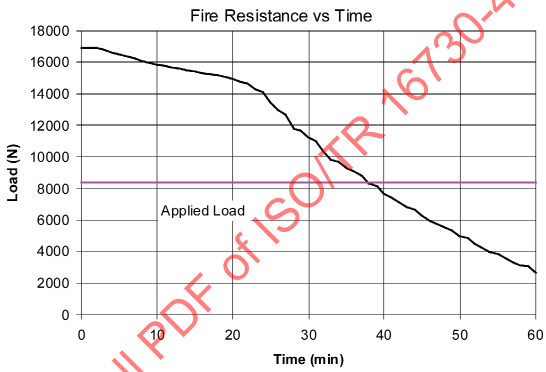


Maximum Deflection vs Time
Deflection (mm)
Model prediction
Experimental data
Time (min)

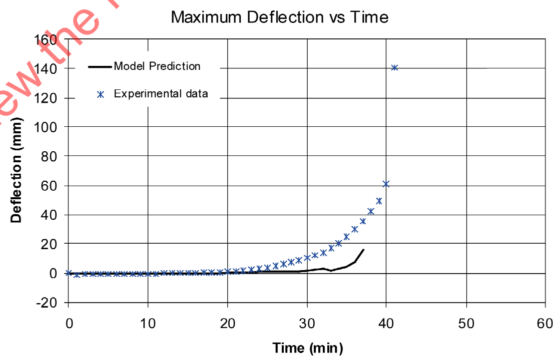
Test a)



Temperature (C)
Time (min)
A
B
Fiurnace Fire
Point A - Experimental
Point A - Model
Point B - Experimental
Point B - Model
Unexposed Side



Fire Resistance vs Time
Load (N)
Applied Load
Time (min)



Maximum Deflection vs Time
Deflection (mm)
Model Prediction
Experimental data
Time (min)

Test b)