Comparison of theoretical and experimental determination of deformations of timber façade elements against wind load

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The current practice is that the deformations of timber façade elements are determined by testing, or they are limited by prescribing dimensions in a very conservative way. To use generic calculation models, suitable for almost all types of windows, approximations deviating from the actual behaviour have to be done. This paper investigates if a calculation method can predict the results from laboratory test with the required accuracy. For that purpose 29 façade elements were tested. Results showed that the calculation method gives a good, slightly conservative prediction for the laboratory tests. As a result, especially for specific project-made windows in small series, the costly laboratory tests can be replaced by calculation.

Key words: Building façades, resistance to wind load, performance assessment, CE-marking

1 Introduction

Timber is a material that historically has been used in building façades. It is considered to be important because of its aesthetic qualities as well as being a natural resource. Timber has its specific structural and durability properties. In depth knowledge on the structural behaviour of timber elements is of great importance to meet the challenges of specific requirements of a construction. This fact is valid when timber is used as a vertical load bearing element within structural system of the building but also when horizontal wind loads on the building envelope are considered.

Building façades are crucial elements that determine the indoor climate conditions, amount of energy consumption and health and safety of the inhabitants. The openings in the facades of buildings have mainly environmental, aesthetic and psychological functions. Mistakes in the design and detailing of façade elements are the root cause of many moisture related problems affecting heating and cooling systems. These mistakes increase the cost of construction and operation, space requirement and can result in indoor quality problems, health issues as well as extra maintenance activities.

Façade elements need to be tested on their performances in a laboratory for a number of requirements to determine the interaction with the whole building shell. For some performance requirements calculation procedures can be developed. For instance, the wind loads on such structures vary widely among regions where the façade elements are used. National codes and standards specify wind loads that can be used as a basis for such a general calculation procedure. Currently, the European Committee for Standardization (CEN) has determined that CE (Conformité Européenne) marking for performance declaration of façade elements will be dealt with by a harmonized standard [1].

This paper presents the study on the assessment of relative frontal deflection of the deforming timber frame members against wind load. Because façade elements are complex assumptions for the distribution of wind load on the overall façade area to the wooden profile elements have to be made. In this paper a number of different window configurations are used as case studies where with known engineering calculation techniques the deflections are calculated.

Resistance to wind load performance is normally determined in a single laboratory test consisting of loadings in terms of air pressure. A 'representative' wind load is applied on the specimen and the deformations of the frame members are measured. Performance declaration shall contain the relevant product properties by giving a specific deflection value in combination with the applied pressure. To make these more easy to interpret for practice performance classes are defined, where the deflection should be within specified limits for a certain pressure.

In this paper is studied how accurate a calculation model can predict the deflection in a laboratory test, with realistic stiffness values as input for the calculations. For that purpose 29 façade elements were tested. The tests are carried out according to the harmonized European product standards [2] and [3] in accredited testing institutes.

2 Calculation method

2.1 *General*

For the proposed calculation method, the façade element is decomposed into smaller sub-elements. The objective is to define simple calculation rules based on structural mechanics that are applicable for different façade compositions. That means that an approach is chosen which is conservative for different composition types. A door or a window wing constitutes the smallest unit surface of the façade as shown in Figure 1a. This unit is called 'casement' or 'sash' for windows and 'leaf' for doors. It is composed of an infill and periphery frame members. Frame is defined as 'component forming the perimeter of a window or door, enabling it to be fixed to the main structure' [4]. Most façade configurations are various combinations of this unit and vertical and horizontal partition profiles which connect these units and the outer most frames. Some simple examples with multi-unit configurations are shown in Figure 1b-c. The deflections are calculated under the assumptions that there are sufficient connections between the outermost façade frame and the building wall and that the infill glasses acts as stiff plates.

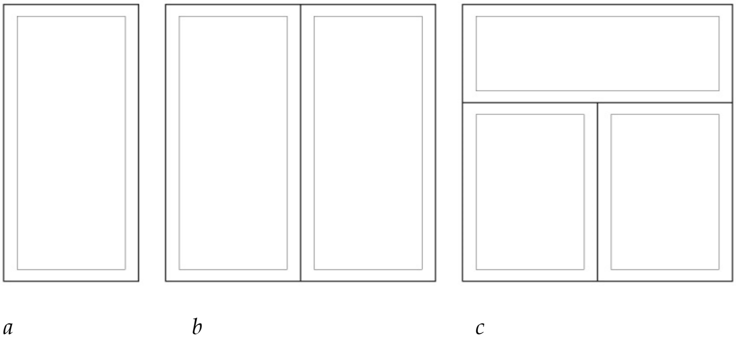


Figure 1. Examples for different configurations for façade elements

A surface pressure, p [N/m^2], is translated into a load model that can be used in a structural design. For all the calculations, the distribution of the wind load is determined according to the envelope method [5]. The envelope method refers to the distribution of the wind load from the infilling panel, e.g. glazing, to the surrounding frame elements. A mechanical model (as presented in the next section) of the window frame with periphery and partition profiles allows for an estimation of the deflections.

Two types of deflections can be distinguished: first, the deflections for the maximum distance between the fixing devices through the perimeter of a casement; second, the deflections for the partition profiles.

In all cases, first the load per length of linear element e.g. frame members is calculated. Second, the deflections due to loads from different casements and reaction forces of elements are computed. The deformation values are added to get the total deformation of the element. Relative frontal deflection is calculated by dividing total deflection by the length of the element.

2.2 *Deflection of periphery profiles*

For a single unit, e.g. casement, the wind load acting on the unit surface is transferred to the periphery frame elements as shown in Figure 2.

The maximum span is the maximum distance between fixing devices which is assumed as a free span. Fixing devices are the components of hardware which fasten the casement to the fixed frame members in its closed position. The maximum distanced fixing devices can be positioned either on vertical or horizontal axis of the unit.

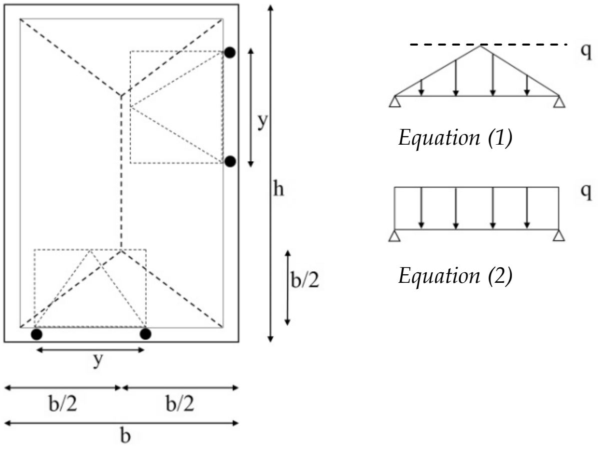


Figure 2. Possible wind load distributions for a single unit

When the maximum distance between the fixing points is equal to *b*, the frame element will be loaded by a triangular shaped wind load with a span of *b*. When the maximum distance between the fixing points is located on the frame between point *b*/2 and *h*-*b*/2 from the corner (in figure 2 this is only possible for the vertical frame element), the frame will be loaded with an equally distributed wind load with a span *h*-*b* However when the distance *y* between the fixings is located as shown in figure 2 in the vertical member the load distribution will be somewhere between two load cases. For simplicity the following procedure is followed:

- The maximum distance *y* is determined
- The deflection due to a triangular load and due to an equally distributed load is

calculated and the average is taken as the result.

This will give conservative values in most cases. For the case where only an equally distributed load works in reality it is slightly underestimating the load, but the fact that the member is a continuous beam over more supports is neglected and counter effects this. The advantage of this approach is that only the maximum distance *y* and the width *b* is necessary for the calculation. The proposed method calculates the deflection between the maximum distance between two fixings assuming that they are located on the casement frame members with the smallest stiffness.

Equation (1) is used for calculating deflection in the middle for a symmetrically triangular shaped load distribution. See figure 1. The value of *q* is the maximum value of the triangular load:

$$\partial_{\text{tri-max}} = \frac{qy}{2}\frac{y^3}{60(EI)_{\min}} \tag{1}$$

Equation (2) is used for calculating deflection in the middle for a rectangular shaped load distribution. See figure 1. The value of *q* is the value of the equally distributed load:

$$\partial_{\text{rect-max}} = \frac{5qy^4}{384(EI)_{\min}} \tag{2}$$

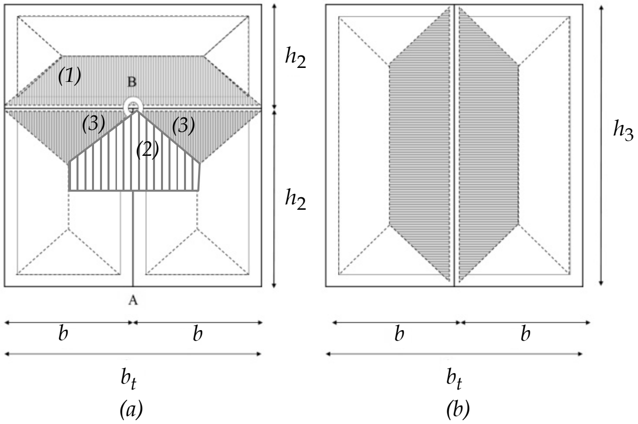
where ∂ = deflection, E = Modulus of Elasticity of the frame element (N/mm^2), I = Moment of Inertia of the frame element (mm^4), y = maximum distance between fixing devices on the frame element (mm), q = maximum value of the triangular load in equation (1) and equally distributed load in equation (2) (N/mm).

If $b < h$ then the load per linear element is calculated as $q = p_w\, b/2$ where q is the load on the linear element (N/mm); p_w is the distributed wind load on surface (N/mm^2) and b is the width of casement (mm). Then the maximum deflection between the fixings of the window is then calculated by following equation

$$\partial_{\text{total-max}} = \frac{\partial_{\text{tri-max}} + \partial_{\text{rect-max}}}{2} \tag{3}$$

2.3 *Deflection of partition profiles*

When there is more than one unit surface adjacent to each other, different load distribution approaches are necessary for on the one hand the façade configurations with parallel frame members with no interconnecting partition members, and on the other hand façade configurations with interconnecting partition members. In this way, all possible rectangular window configurations can be modelled and calculated. Examples and possible load distributions for both cases are shown in Figure 3. Hence, for deflection analysis, the indirect and direct loads transferred by a specific frame element should be analyzed. This combination of loads can be critical for members that are affected by loads from adjacent surfaces and interconnecting frame members. The starting point in the calculations is that all the connections between the members are considered to be hinges in the plane perpendicular to the load direction.



(a) *(b)*

Figure 3. Load distributions on different configurations with vertical and horizontal partition members

The maximum deflection on vertical partition member sown in figure 3b can be calculated with equation :

$$\partial_{vert-part} = q h_3^4 \frac{25 - 40\left(\dfrac{b}{2h_3}\right)^2 + 16\left(\dfrac{b}{2h_3}\right)^4}{1920 (EI)_{vert-part}} \tag{4}$$

where for the vertical partition member; $\partial_{vert-part}$ = deflection in the middle of the span, $(EI)_{vert-part}$ = bending stiffness, h_3 = length.

The deflection of a horizontal partition member, as shown in Figure 3a, is calculated by the summation of the deflections due to three load cases: one trapezoid load area from top unit *(1),* one point load at the point B due to the reaction force due to load distribution on *(2)* and two triangular load areas from the two below units *(3).*

Deflection at mid-span of horizontal partition member due to load distribution *(1)* from the top unit can be calculated as:

$$\partial_{\max(l)} = q_{(l)} b_t^4 \frac{25 - 40\left(\frac{h_1}{2b_t}\right)^2 + 16\left(\frac{h_1}{2b_t}\right)^4}{1920(EI)_{horz-part}} \tag{5a}$$

where $q_{(1)} = p_w\ h_1/2$, and b_t = span of the horizontal element.

Then, deflection of *(2)* at mid-span due to the reaction force R_B can be calculated as;

$$\partial_{\max(2)} = \frac{1}{48}\frac{F_B\, b_t^3}{(EI)_{horz-part}} \tag{5b}$$

where the reaction force $F_B = R_B = R_A = q_{(2)}\ (0.5\, h_2 - 0.5\, b) + q_{(2)}\ 0.25\, b$

where $q_{(2)} = p_w\ b$, and b = width of one casement and b_t = span of the horizontal element.

Deflection due to Load distribution *(3)* from below units can be calculated with Equation 7. The load with two triangle load distributions can be replaced by subtracting a triangular load from a trapezoid load, with $q = 2\, q_{(3)}$.

$$\partial_{\max(3)} = 2q_{(3)} b_t^4 \frac{25 - 40\left(\frac{b}{2b_t}\right)^2 + 16\left(\frac{b}{2b_t}\right)^4}{1920\ (EI)_{horz-part}} - \frac{2q_{(3)}b_t}{2}\frac{b_t^3}{60(EI)_{horz-part}} \tag{6}$$

where $q_{(3)} = p_w\ b/2$, and b_t = span of the horizontal element.

The total deformation on the transom (the horizontal partition member) is the summation of these three deformations as in Equation 8 and relative frontal deformation is calculated by dividing the deflection by the total length of horizontal partition member.

$$\partial_{\max;\text{total}} = \partial_{\max(1)} + \partial_{\max(2)} + \partial_{\max(3)} \tag{7}$$

3 Comparison of calculation results with experimental data

In the framework of the EU-project "ECWINS"[6] 29 windows were tested experimentally. The measured deflections are compared with values found with the calculation method. In the experimental study, the deflection of a window frame element is determined by applying a static pressure difference on the external face and the internal face of the window with certain pressure steps as defined in [2]. The tests were conducted with full size specimens with various different configurations in three testing institutes in Italy (CNR-Ivalsa), Hungary (UWH) and Finland (VTT). The test setup comprises fixation of test specimen to the test chamber and placement of measurement devices such as dial gauges for measuring displacements as shown in figure 4.

Figure 4. Test set up and placement of measurement devices according to EN 12211:2000 [2]

Firstly, the results of the approach described above are presented by comparison of calculation of the deflection and measured deflection in the two example configurations. Secondly, the results on overall data set are discussed.

The examples selected are: a two unit window, with layout in Figure 1b, wood species larch (specimen A); a three unit window, with layout in Figure 1c, wood species spruce (specimen B). These examples are chosen as they provide a good picture for the most deflecting elements in any window configuration. The deflection values computed by the model are compared with the values recorded during laboratory tests for positive pressure.

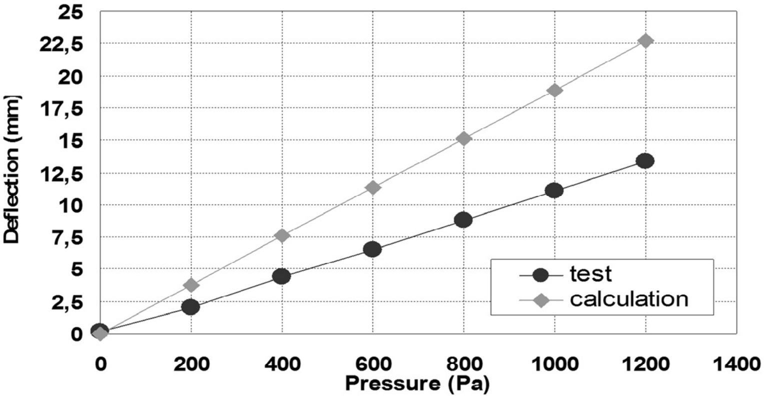


Figure 5. Deflection of vertical partition member for specimen A

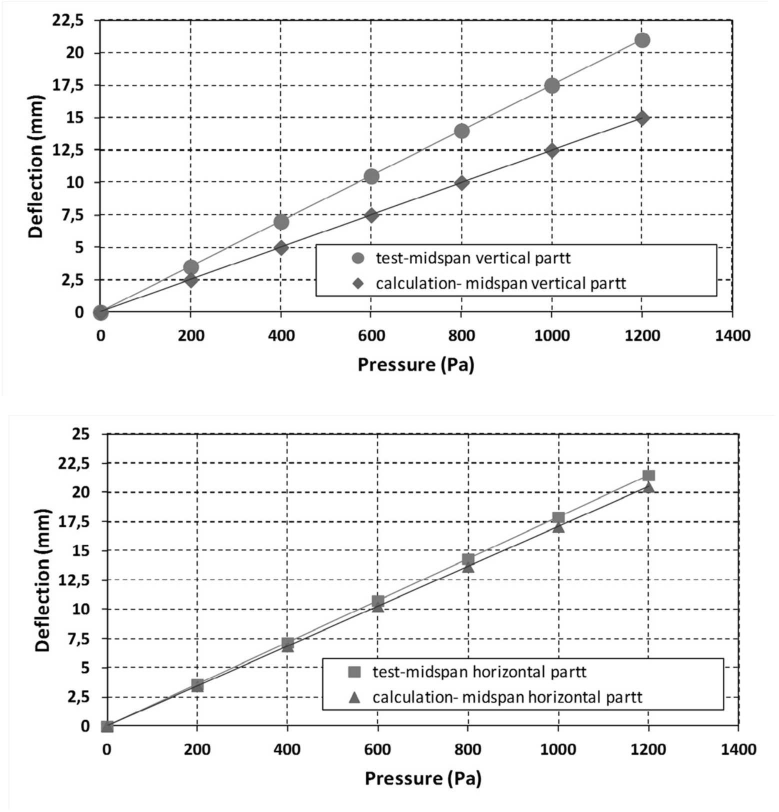


Figure 6. Deflection of vertical partition members (top figure) and horizontal partition members (figure below) for specimen B

The results for deflections with tested values and calculated values are given in Figure 5 and Figure 6 respectively. It can be seen that for specimen B, the results for deflection of the horizontal partition member is almost the same values with tested values, whereas the calculated deflection values of the vertical partition member underestimate the test results. For specimen A, it can be seen that the calculated value overestimates the tested deflection of vertical partition member. Possible explanations for the differences can be :

- The difference in the mechanical scheme in the calculation model compared to the realty.
- The Modulus of Elasticity of individual elements was not measured before the manufacturing of the window. The average Modulus of Elasticity of the strength class the elements were graded to was used in the calculation. Since timber is a natural material, the actual Modulus of Elasticity of the elements may vary from the mean value of a strength class.
- The influence of the mounting of the specimens in the test set-up. A round robin test between the 3 testing institutes showed that small differences in the mounting procedures, can have a significant effect on the test result.

A total of 29 façade elements were tested during the experimental study, with 16 single and 13 multi unit configurations. The specimens were manufactured with solid timber elements of wood species: spruce, pine, larch, oak, meranti, fir and sapupira.

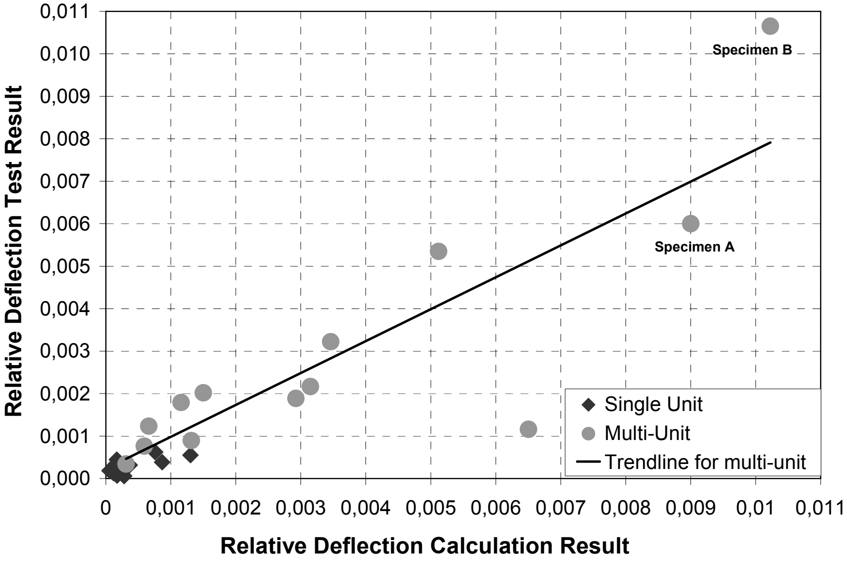


Figure 7. Deflection assessment results by test and calculation methods

Figure 7 shows the tested and calculated results for the relative frontal deflection which was obtained by dividing the most deflecting element by its span at maximum pressure levels; 1200 Pa or 800 Pa. It can be seen that single unit configurations have very low deflection values. This is due to relatively smaller spans, defined as maximum distance between fixing devices, through the perimeter of the frame. For multi unit configurations, the maximum deflections are at mid-span of vertical or horizontal partition members. The position depends on the cross-sectional dimensions and length of these members. Figure 7 shows that calculation results gives good prediction of the laboratory test results, taking into account the possible errors in calculation and testing as described before. The measured deflections are on average about 80% of the calculated deflections. This is on the safe side, but more important, this is a general trend for all tested windows. That gives confidence that the chosen calculation method is suitable for a safe prediction of the deflections.

4 Conclusions

A calculation model has been presented to determine the wind load on various façade configurations and elements. The maximum deflection values on a set of timber façade elements are determined by this method. 29 full size specimens were tested and the results were used for validation of the proposed calculation method. The results show that the calculated deflection values followed the same trend as the deflections found in full size laboratory tests. The measured deflections were on average about 80% of deflections calculated with the proposed method.

The experimental verification shows that the chosen mechanical schemes with hinges in the plane perpendicular to the load direction at all connections between the members is an approach that gives conservative results, but close enough to the measured values to use the calculation method instead of an experimental test. This is particularly important in regard with the obliged CE-marking for windows according to EN 14351 [7] where the deflections under wind loads of the product is one of the properties to be listed. For project-made windows a laboratory type test is much too expensive, especially for small companies. With the proposed calculation method, which can be used in accordance to [7] project-made windows can be optimized. When the modulus of elasticity of an individual element is measured and threshold values are defined further optimisation is possible. In the ECWINS project the method was incorporated in a software tool for this purpose.

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