Summary
An office building was rebuilt by adding three stories on top of the roof. The construction used was a steel framework combined with prefabricated wooden floor elements. After moving in the tenants complained about annoying vibrations in the floors. To investigate to what extent the steel framework and the wooden elements, respectively, contributed to the deflections and the vibration response of the floor system, an analysis by means of the finite-element method and calculations by hand were carried out. Both static and dynamic load effects were studied. The analysis shows that the deflection contribution of the steel framework should be considered in the calculation of the total deflection of the floor element. New guidelines should be written that takes the combined effect of the floor framework and the supporting structure into account.

Keywords: prefabricated, wooden floor element, vibration, design criteria, guidelines

1. Introduction
Since the Swedish fire regulations changed in 1994 from material-prescribed requirements to function based ones, it is now permitted to build higher buildings of wood than two stories. The problem of fire safety for wooden buildings is today solved for several cases. Also research and development concerning problems with acoustics of buildings have made substantial progress. There are, however, still problems to be solved, like footstep impact sound and flanking transmission. A third problem area to be treated is the resilience and the vibrations of lightweight floors in a building. These problems are today of great interest due to an increasing demand of open flexible floor areas, with longer spans as a consequence. Further, more efficient material utilization and better optimisation techniques will lead to the use of more slender structures. This will require better and more complete design guidelines and criteria that make it possible for designers to verify the performance of floor systems considering human induced vibrations. The use of prefabricated lightweight wooden floor elements is increasing in Sweden. A major part is used in residential buildings, but also the use in office and public buildings is rising. Lightweight wooden elements are increasingly used when clients wish to add floors to an existing building. Mixed-use structures of steel and wood occur frequently as an alternative to the traditional concept of a steel framework and prefabricated concrete elements. The question dealt with in this paper is what happens with the performance due to human induced vibrations when the heavy concrete elements are replaced by lightweight wooden elements.
2. A Case-Study

2.1 Background and Aim
An office building was rebuilt by adding three stories on top of the roof. The building was originally built of concrete and the weight of the added floor structures had to be minimised so that the load bearing capacity of the lower part of structure was not exceeded. The solution was in this case to use a steel framework combined with prefabricated wooden floor elements. The steel framework and the floor elements were designed and delivered by different contractors. The new top floors of the office have an open layout that in principle consists of an office area with groups of desk places along the outer long sides of the building as shown in Figure 1 a.

![Figure 1](image)

**Figure 1**  
a) Principal layout of building.  
b) Steel framework and principal placement of floor elements.

In the inner central part of the building there is a common area and on both sides of this area (in connection to the office area) long corridors are running along the whole building. A few months after the tenants moved into the office they complained about annoying vibrations. People walking along the corridors, subjecting the floor structure to dynamic loading, caused the annoying vibrations. These vibrations were transmitted from the floor to the desks in the office area and through the desks to the light flat screens on the desks, making them vibrate. In order to get the tenants satisfied with the performance of the floors the builder had to make an expensive reinforcement of the whole structure.

The aim of this work is to clarify to which extent the steel framework and the wooden elements, respectively, contributed to the deflection and vibration response of the floor system.

2.2 Structural Parts

2.2.1 Wooden Floor Elements
The floor framework consists of prefabricated elements as shown in Figure 2. The dimension of the beams is 45x220 mm and the spacing 180 mm. The timber is of strength class C18 according to EN388. The span of the elements is 5.1 m and the width 2.1 m except for those cases where the width has to be adjusted to the width of the bay. The floor sheets consist of a 22 mm load bearing particleboard P5 for humid conditions (V313 flooring grade chipboard). The board is glued to the beams with PVAc glue Cascol 3303. The gluing is complemented with screws to ensure a sufficient pressure in the glueline during hardening. The outer beams along the edges are screwed with a spacing of 150 mm and every second inner beam is screwed with a spacing of 600 mm.
The elements are simply supported on the L-profiles welded to the secondary beams as shown in Figure 3 a. To satisfy the requirements of progressive collapse every element is fastened with two steel brackets. The brackets are screwed to the floor elements with a hexagon head wood screw and to the supporting steel profile with a self-drilling steel screw.

Figure 2 Section through a floor element. (Only load-bearing parts shown.)

2.2.2 Steel Framework

The steel framework consists of bearing I-profile columns that are continuous throughout the height of the new on-built building. The spacing of the columns along the building is 8 m as shown in Figure 1 a. In the transverse direction the column spacing is 10.4 m. There are only three rows of columns, one at each facade and one in the middle of the building. The outer columns at the facade are HEA280 profiles and the inner columns are HEA320 profiles. The primary beams across the building consist of HEA400 profiles welded to the columns, which means that they can be regarded as continuous at the middle column. The secondary beams in the length direction of the building divide the bays across the building into equally spaced smaller bays of 5.2 m width. The outer secondary beams at the facades consist of IPE400 profiles and the inner ones of HEA340 profiles. They are mounted to the columns and to the primary beams by means of bolted joints as shown in Figure 3 b.

As can be seen in Figure 3 b the upper flanges of the secondary beams were mounted on the same level as the upper flanges of the primary beams. L-profiles are welded to the bottom flange of the secondary beams as shown in Figure 3 a. These profiles provide support for the floor elements. This means that the floor elements are not continuous between the bays in the floor system. The only connection between the elements is a strip of particleboard over the supporting beams glued and screwed to the elements.

Figure 3 a) Eccentric placement of the concentrated load on the secondary beam. b) Eccentric placement of the concentrated load on the primary beam.

3. Design Guidelines and Criteria

Both static and dynamic criteria are used in the Swedish guidelines in order to avoid harmful and annoying vibrations in the design of wooden floors. The methods are similar to the ones given in Eurocode 5. The static design criterion limits the deflection to 1.5 mm caused by a concentrated load 1 kN in the middle of the span of a simply supported beam. Load sharing by adjacent beams is allowed for in the calculation of the deflection. The dynamic design guidelines and criteria are based on investigations by Ohlsson [1]. In practice they are limited to residential buildings with span less than four meters and frequencies over 8 Hz. In Sweden there are no design criteria for floors with larger spans than four meters and floors with long free surfaces that may be subjected to walking loads. Such loads must be considered in office and public buildings. In these cases the designer has to compare design results with results obtained from built projects with similar layout and loading.
4. Analysis and Results

4.1 Static Loading

4.1.1 Finite-element modelling

The midspan deflection of the wooden floor element, due to a 1 kN concentrated load placed over one of the beams in the middle of the floor element, was calculated by means of a finite-element model. The element was assumed to be simply supported on rigid supports. The finite-element analysis was applied to make clear how many of the adjacent floor beams that contributed to the load sharing. In the modelling full interaction between the beams and the particleboard was assumed. The program used was ABACUS [2] and the floor elements were modelled with solid 20-node elements with reduced integration. The timber was modelled as a simplified orthotropic material with density and mechanical properties as listed in Table 1.

Table 1 The density and the mechanical properties used in the modelling of timber beams.

<table>
<thead>
<tr>
<th>Density (kg/m$^3$)</th>
<th>Modulus of elasticity (MPa)</th>
<th>Poisson’s ratio</th>
<th>Modulus of shear (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_L$</td>
<td>$E_R$</td>
<td>$E_T$</td>
</tr>
<tr>
<td>320</td>
<td>9000</td>
<td>300</td>
<td>300</td>
</tr>
</tbody>
</table>

The values used are assumed to correspond to the mean values of timber strength class C18 in European standard EN338. The particleboard is modelled as an isotropic material with a modulus of elasticity of 3000 MPa and a density of 700 kg/m$^3$ according to the manufacturer. The Poisson’s ratio was set to 0.3.

In Figure 4 a the midspan deflection of the beams is shown when in the floor element subjected to a 1 kN concentrated load. The maximum deflection is 0.91 mm which is less than the limiting value of 1.5 mm. It can be seen in the figure that several of the middle floor beams share the loading, but the beams at the edges are only slightly influenced. To verify the hand-calculation (section 4.1.2) of the secondary beam and to analyse the torsional behaviour and what effect the L-profiles have on the deformations the steel beam was also analysed by the finite-element method. In Figure 4 b the deformation of the secondary steel beam is shown. The modelling showed that the L-profile and steel plates welded to the beam do not contribute much to the rotational stiffness of the beam, but increase the local bending stiffness of the flange. The midspan deflection at the concentrated load of the modelled beam was 0.25 mm, which agreed well with the hand-calculated values.

Figure 4 a) Deformation of the floor element due to 1 kN concentrated load.  
b) Deformation of the secondary steel beam due to an eccentric concentrated load.
4.1.2 Hand-calculation

By calculating the deflections of the primary and secondary beams an estimate could be made of their contribution to the total deflections. The beam deflection was calculated for three different load cases. In all these three cases a concentrated load of 1 kN was used and it was placed in the middle of the span of the floor element or the beams as shown in Figure 1 b. Both deflection due to bending and torsion of the beams were considered. In the calculation of deflections due to torsion the eccentricities according to Figure 3 a and b were used. The vertical movement due to torsion was calculated at the applied load. The results are presented in Table 2 below. In the last column the total deflections are given. For the first load case the deflection due to the steel beams is summed up separately.

Table 2 Vertical deflection of steel beams and floor element due to 1 kN concentrated load.

<table>
<thead>
<tr>
<th>Load case</th>
<th>Structural component</th>
<th>Deflection due to Bending (mm)</th>
<th>Torsion (mm)</th>
<th>Deflection of structural component (mm)</th>
<th>Total deflection at loading point (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Secondary beam</td>
<td>0.082</td>
<td>0.156</td>
<td>0.283</td>
<td>Σ 0.351</td>
</tr>
<tr>
<td></td>
<td>Primary beam</td>
<td>0.055</td>
<td>0.013</td>
<td>0.068</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Floor element</td>
<td></td>
<td>0.91</td>
<td></td>
<td>Σ 1.261</td>
</tr>
<tr>
<td>2</td>
<td>Secondary beam</td>
<td>0.164</td>
<td>0.312</td>
<td>0.476</td>
<td>Σ 0.612</td>
</tr>
<tr>
<td></td>
<td>Primary beam</td>
<td>0.110</td>
<td>0.026</td>
<td>0.136</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Primary beam</td>
<td>0.220</td>
<td>0.052</td>
<td>0.272</td>
<td>Σ 0.272</td>
</tr>
</tbody>
</table>

The deflection of 0.91 mm of the floor element is calculated assuming rigid support conditions and that the first load case gives the contribution of the steel framework. This contribution is almost about one third of the total deflection. The second load case shows that the contribution from the steel framework increases the nearer the load is placed to the secondary beam. On the other hand, the deflection of the floor element will decrease the nearer the load is placed to the supporting beam.

4.2 Dynamic Loading

In order to study the influence of the support conditions on the dynamic response of the floor elements, finite-element analyses were carried out both with rigid and semirigid support conditions. For each support condition the peak amplitude, velocity and acceleration were determined. As an example of the ongoing study some vibration modes are shown in Figure 5 for a floor element with two edges simply supported and the other two edges free. The first mode without any additional dead weight had a frequency of about 17 Hz. If the dead weight is increased a lower frequency of will be obtained. The frequencies of the six lowest vibration modes are given in Table 3.

Table 3 Frequencies of the six lowest vibration modes

<table>
<thead>
<tr>
<th>Mode no.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>17.1</td>
<td>17.7</td>
<td>29.0</td>
<td>35.6</td>
<td>44.0</td>
<td>55.4</td>
</tr>
</tbody>
</table>
5. Concluding remarks

A load applied on a floor element will affect persons standing nearby on the floor in two different ways. If the person stands nearby in the lengthways direction of the floor element he will be affected by the deflection immediately. If the person stands at some distance transverse to the span direction he will sense the deflection in an indirect way by the movement of the floor element supports. In the latter case the deflection will much depend on the flexibility of the support.

The combination of light weight floor elements and supporting steel framework is a fairly new concept compared to heavy concrete elements combined with steel framework. The fact that the wooden elements are light implies that uncontrolled motions by dynamic loading are easier introduced than in the case of heavy and stiff concrete elements. If the steel framework supporting the wooden floor elements is not stiff enough the consequence may be severe problems with annoying vibrations.

The deflection contribution of the steel framework should be considered in the calculation of the total deflection of the floor element. Thus in order to avoid annoying vibrations sensed by the user, the analysis should not refer to the wooden floor elements only, but the surrounding steel framework must also be considered. This means that in the design of such structures of mixed materials new type of guidelines should be written that take into account the combined effect of the floor framework and the supporting structure.

6. References
