Imperfection measurements for trusses using nail plates
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ABSTRACT

Within the scope of a research project, deformations of constructed nail-plate trusses are first measured and then modeled as imperfections using a non-linear finite element analysis. The statistically evaluated results will be used to develop simplified substitute imperfections for design purposes.

INTRODUCTION

Building systems today require for a high degree of flexibility if the solutions are to be optimal in terms of efficiency, economy and ecology. Girder systems using nail plates count among the most effective roof structures for spans of up to 30 m. Designed with a view to optimize material volumes, they result in thin and light-weight components of high strength and rigidity when responding to actions along the girder plane. This presupposes, however, that they are considered as perfectly plane systems.

Imperfections, which may, for instance, be due to the material and/or production process used, and also to inaccurate installation on site, always subject the trusses to loads that also act in a direction perpendicular to the plane of the truss. Under such conditions the strength and rigidity of the truss itself may not be adequate.

Is it appropriate to make the same imperfection assumptions for this special industrial-fabricated systems as for other industrial-fabricated constructions like glued laminated timber (Kessel 1996)?

Bainbridge et al (1997) tried to avoid fabrication-related imperfections in their full-scale testing. Thus their results are only of academic interest.

The combined effect of battens, purlins, and bracing systems, which, acting together with the truss, produces a three-dimensional load-bearing system that will safely transmit loads into the substructure. For reasons of cost it is, for the time being, ineffective to subject individual three-dimensional systems to non-linear analyses for determination of the load-bearing behaviour. The load conditions affecting the three-dimensional structure because of imperfections and the resultant geometrical non-linearities, therefore, have to be determined from the effect of equivalent in-plane and out-of-plane loads acting on their respective load carrying systems (for instance, the truss and its bracing).

Currently hardly any data are available on imperfections (skewness and initial bow) in existing structures using nail-plate trusses. This research project will analyse such aspects as imperfection size and shape to derive recommendations for

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Figure 1: Hall for timber storage
standardisation from the findings. In this work „skewness“ refers to an out-of-plumb imperfection of the truss.

In view of the above, a statistical survey was made to obtain data on imperfections in existing nail-plate structures. For a number of structures selected at random, truss skewness and bow curvature under actual loads as well as any other imperfections were measured. This was followed by a non-linear analysis of the load-bearing structures to arrive at conclusions on the existing initial deformations. Only the survey and statistical analysis of imperfections is reported here.

**IMPERFECTIONS**

In civil engineering one speaks about imperfections or initial deformations, which means a deviation of built construction from the ideal material properties and shapes assumed in the design process. Therefore imperfections have to be subdivided into material and geometrical imperfections.

Since wood is a natural material, imperfections are caused by defects such as variable density, knots, sloping grain, spiral grow, and warping. Nearly orthotropic material behavior also complicates the analysis.

Geometric imperfections define the second group. They were determined within the scope of this research project. For a better understanding we distinguish between local and global imperfections. An initial bow imperfection of the top chords (Figure 2) and bottom chords (Figure 3), as well as a resulting skewness of the diagonals, belong to the group of local imperfections.

An equivalent load that causes a specific initial bow imperfection, is normally applied to account for an initial bow imperfection of the top chords. This equivalent load is determined for a strut with hinge support at both ends and a constant axial force. So far we do not know whether the equivalent load is on the safe side or not. However, Figures 2 and 3 illustrate that a initial bow imperfection of the top or bottom chord causes a direct skewness of connected diagonals and the resulting restoring force, depending on the existing axial force.

Global imperfection defines a total inclination of the girder relative to the points of support as shown in Figure 4.

A subdivision into local and global imperfections is used to explain the impact of these imperfections on the structure as a whole. Substituting the imperfections with load groups makes it clear that skewness causes external forces, whereas initial bow imperfection results in only internal stresses.

In reality, both kinds of imperfection occur at the same time. For economic reasons, it is not possible to investigate all pre-deformations that occur, and to consider them within the analysis of the structural system. Therefore, in building codes these two imperfection groups are distinguished as well.
INVESTIGATION OBJECTIVE

The results of this research project will be recommended values for substitute loads that account for imperfections (inclinations and initial bow) for designing structures. A statistical survey was carried out to determine these values.

The aim of this investigation was to numerically describe imperfections of nail-plate trusses for double pitched roofs for the first time. The total number of nail-plate trusses is so great that distribution parameters had to be determined by taking a random sample. The method for choosing random samples is a multi-step random selection (Figure 5).

The first step was a random selection of six companies (nail-plate truss manufacturers) out of the entire population of companies. The next step was a random selection of construction projects (A-Z) of each selected company. Projects were only considered if they allow imperfection measurements. These include projects during erection, or buildings in which the truss structure is open, or at least accessible.

No statistical survey on the problem of imperfections of nail-plate trusses is currently available. As the result there are no usable average values from other surveys. However, it can be assumed that standard deviations determined for imperfection measurements on wood columns (Ehlbeck, Blaß 1987) are comparable with expected standard deviations for nail-plate trusses.

The size of the random samples can be determined for a certain confidence level. It can be shown that 35 measurements, as a random sample, are sufficient for the characteristic to be investigated.

MEASUREMENT EXECUTION

Measurements were carried out with a theodolite Th 2 produced by Carl Zeiss. The theodolite is installed beneath the measured truss, within a distance of approximately 5-20 cm from the plane of the truss. Figure 6 shows the vertical plane created by the theodolite, as well as the real location of the measured truss in relation to it.

Based on this plane, y-coordinates of the truss’ joints can be determined. Distances that are to be measured are also shown in Figure 6. If the support points of the bottom chords are fixed, it is possible to determine the skewness of the truss or the initial bow imperfection of the chords, by direct measurement.

All data is recorded in a special protocol (Table 1).
Table 1: Measurement Data

<table>
<thead>
<tr>
<th>Date</th>
<th>Project</th>
<th>Truss</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.01.1999</td>
<td>Sorting Facility</td>
<td>8</td>
</tr>
</tbody>
</table>

Adoption of data from Measurement Records

<table>
<thead>
<tr>
<th>Measurement Point</th>
<th>Measurement I [cm]</th>
<th>Measurement II [cm]</th>
<th>Average from</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper Face of Top Chord</td>
<td>Bottom Edge of Top Chord</td>
<td>I and II</td>
</tr>
<tr>
<td>1 (Eave A)</td>
<td>16</td>
<td>15.1</td>
<td>15.55</td>
</tr>
<tr>
<td>2</td>
<td>13.3</td>
<td>13.1</td>
<td>13.2</td>
</tr>
<tr>
<td>3</td>
<td>14.6</td>
<td>14</td>
<td>14.3</td>
</tr>
<tr>
<td>4 (Ridge C)</td>
<td>11.3</td>
<td>10.9</td>
<td>11.1</td>
</tr>
<tr>
<td>5</td>
<td>7.8</td>
<td>7.6</td>
<td>7.7</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>9.1</td>
<td>9.55</td>
</tr>
<tr>
<td>7 (Eave B)</td>
<td>5.1</td>
<td>3.5</td>
<td>4.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Upper Face of Bottom Chord</th>
<th>Bottom Edge of Bottom Chord</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 (Eave A)</td>
<td>16</td>
<td>15.1</td>
</tr>
<tr>
<td>9</td>
<td>12.3</td>
<td>12.5</td>
</tr>
<tr>
<td>10</td>
<td>11.7</td>
<td>12</td>
</tr>
<tr>
<td>11</td>
<td>8.1</td>
<td>8.4</td>
</tr>
<tr>
<td>12</td>
<td>5.6</td>
<td>5.1</td>
</tr>
<tr>
<td>13 (Eave B)</td>
<td>5.1</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Only the y-coordinate of the joint positions are measured for the truss, since the x- and z-coordinate data can be taken from truss design records. Measuring the trusses in-plane was not possible for practical and time reasons.

Furthermore, special features are recorded concerning the method of bracing, the structure in its entirety, and existing loads and actions. Cross-sectional dimensions of chords and struts are measured at randomly selected trusses.
PROJECTS (EXAMPLES)

**Project O:** Supermarket 5 (Figure 7)
Newly built gabled-roof structure;
Two triangular trusses measured in the middle area and
one truss measured at the bracing location;
Span = 24.5m, Roof slope = 20°

![Figure 7: Supermarket 5](image)

**Project P:** Supermarket 6 (Figure 8)
Newly built hipped-roof structure;
Triangular truss, measured in the middle area and one truss measured at the bracing location;
Span = 29.7m, Roof slope = 21°

![Figure 8: Supermarket 6](image)

**Project Q:** Hall for timber storage 2 (Figure 9)
Completely open storage hall with overhang at the sides;
Two trusses measured between two bracing locations
Span = 27.1 m, Roof slope = 15°

![Figure 9: Hall for timber storage](image)

DATA PROCESSING

For use in the non-linear analysis, the survey data, which includes the offset of the vertical plane established by the theodolite from the plane of the truss, must be post-processed. To do this, the data must be numerically converted to the plane defined by the ridge point and both eave points. In the following, the procedure for such a conversion is given for a triangular truss. Except for a few changes, this procedure can be applied to any kind of truss.
The plane created with the theodolite is translated until it touches eave point A (Figure 10).

\[ a_i' = a_i - a_1 \quad i=1,\ldots,n \]

Figure 10: Plane translation

Next, the theodolite plane is rotated about the z axis into eave point B (Figure 11).

\[ a_i'' = a_i' - a_n \frac{L_i}{L} \quad i=1,\ldots,n \]

Figure 11: Plane rotation about the z axis

At last, the plane is rotated around axis A – B, into the ridge point C. Now the measured initial bow imperfections of all chords, as well as the measured skewness of the truss can be recorded.

Unavoidable measurement errors are included in the survey data and must be filtered out prior to non-linear analysis. Then, to evaluate the post-processed imperfection results statistically, it will be necessary to establish a reference value for skewness and initial bow imperfection that will permit data from different trusses to be compared on the same basis.

For an approximate description of bow, a function is needed that describes chord deformations to the sides as realistically as possible. A half-sine function: \( y(x_i) = V \cdot \sin(\pi \cdot \frac{x_i}{L}) \), and a complete sine curve: \( y(x_i) = V \cdot \sin(2 \cdot \pi \cdot \frac{x_i}{L}) \) are possible candidates. However, neither function can accurately measured values for all cases (see Figure 12).

Figure 12: Insufficient approximation of a measurement series
A realistic recording of existing skewnesses is not ensured with these functions. Instead, bow imperfections are averaged using the sine function, which is likely to cause faulty results.

A multiple-term sine series approach was, therefore, used to better represent actual initial bow conditions and to automate the evaluation process. The approach can be adjusted to every deformation situation encountered.

A general function of the form: \( y(x) = \sum_{j=1}^{m} \left( V_j \cdot \sin\left( j \cdot \frac{\pi \cdot x}{L} \right) \right) \) contains an arbitrary number of terms. However, during processing it became clear that a four-term approximation is sufficient. It contains two simple symmetric terms, as well as two unsymmetrical terms. The target function (minimization of the squared spaces) for which variables \( V_1, V_2, V_3 \) and \( V_4 \) have to be defined, reads as follows:

\[
\sum_{i=1}^{n} \left[ y_i - V_1 \cdot \sin\left( \frac{\pi \cdot x_i}{L} \right) - V_2 \cdot \sin\left( 2 \cdot \frac{\pi \cdot x_i}{L} \right) - V_3 \cdot \sin\left( 3 \cdot \frac{\pi \cdot x_i}{L} \right) - V_4 \cdot \sin\left( 4 \cdot \frac{\pi \cdot x_i}{L} \right) \right]^2 = \text{Min}
\]

By analyzing measuring results with this function, it became possible to split geometric imperfections into their symmetrical and unsymmetrical parts and to give each the appropriate magnitude. This is very useful for clear display of the deformation (Figure 13).

![Figure 13: Imperfection display as the sum of symmetric and unsymmetrical parts](image)

**CALCULATING IMPERFECTIONS**

The measured deformations contain not only imperfections, but also deformations caused by other actions. Therefore, actions that were present during measurements must be taken into account. Those are actions due to dead loads, such as roofing and suspended ceilings, as well as snow loads and wind loads.

The wind pressure is calculated according to the Beaufort scale (1857). This scale makes it possible to estimate wind forces without special tools, simply by observing the nature. A conversion table is then used to determine wind speeds and thus to determine stresses that must be applied.

Calculation are carried out on an imperfect three-dimensional system, based on a non-linear theory. In this case imperfections are changed in an iterative way until final deformations under actual forces match the measured values.
STATISTICAL ANALYSIS

Imperfections in nail-plate trusses are symmetrically distributed about a mean described by a „perfect“ truss (one without imperfections). Assuming that the distribution is also normal, standard deviations can be estimated based on random samples. The average skewness taken from the population is zero, since the average of all trusses is straight and since trusses will deform in both directions. The same conditions apply for bow imperfections. Imperfections are used for analysis by considering signs.

For every project the theodolite’s location was chosen at random. Consideration of signs (+/-), based on the appropriate installation, was only possible within one project. To take this effect into account during the analysis, results were mirrored. This way for evaluation, all measured values are counted with a positive and a negative sign. A preliminary distribution for skewness is displayed as shown in Figure 14.

CONCLUSIONS

Post-processing of the measured data shows that each of the three geometric imperfections is possible. For trusses with spans over 15 m, the approximation for initial bow imperfection as a simple curve is unrealistic. However, for design of nail-plate trusses we will further use this simple approach in the form of an equivalent load. In addition the skewness of trusses must be included in the design procedure of these structures. But at the time being it is not.

REFERENCES


Beaufort, F. 1857. original reference not available, see instead: [http://www.im.nbs.gov/beaufort.html](http://www.im.nbs.gov/beaufort.html)

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