Reliability Based Design Of Timber Sheet Pile Walls

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SUMMARY

About 60% of the 4000 km engineered sheet pile walls in the Netherlands are made of timber. The species most applied for this application are azobé (Lophira Alata) and treated pine (Pinus sylvestris). In order to optimise material use as much as possible the fifth percentile strength value of the system of coupled boards has been determined using a combination of experimental tests and numerical Monte Carlo simulations. The experiments consist of four point bending tests on single boards as well as on parallel boards coupled by tongue and groove. The actual fifth percentile strength value of the individual boards has been determined. The increase in strength as a result of the system effect is written as a load sharing factor on the fifth percentile strength value of the single boards. Load-sharing factors have been derived for the two species and were found to be 1.17 for azobé and 1.33 for treated pine.

1. INTRODUCTION

Load sharing of boards can give considerable characteristic strength increase. Boards coupled by tongue and groove are used in several types of systems, one of which is a sheet pile wall. Sheet pile walls are widely used to protect waterways. In the Netherlands a total length of 2400 km is made of timber. The most common timber species used for this purpose are azobé (*Lophira alata*) and treated pine (*Pinus sylvestris*). The depth of the sheet pile wall varies with a maximum of about 8 metres. A schematic representation of a timber sheet pile wall is shown in figure 1.

2. DESIGN PHILOSOPHY

With the introduction of LRFD-codes the fifth percentile strength value is used for material properties. However, reliability based design philosophy allows for the introduction of system factors where members are acting parallel. This parallel action can increase the design strength. Substantial increases in design strength can be obtained, depending on the plasticity in the materials and the variation in material properties. In this study plasticity in individual boards as well as in a system of parallel boards have been determined. The results of the tests have been used in Monte Carlo simulations where the effects of the number of parallel acting boards and board thickness have been analysed. For practical purposes the results of the study are presented as load sharing factors for the species studied. In its most general form the strength requirement for a structure is written as follows:

$$\frac{R}{\gamma_M} \geq \gamma_s S \qquad (1)$$

in which:

R	is the strength of the system;
S	is the load on the system;
γ_M	is the material factor;
γ_s	is the load factor.

For the strength of systems where members are acting in parallel equation 1 can be modified to:

$$k_{ls} \frac{R}{\gamma_M} \geq \gamma_s S \qquad (2)$$

with in addition to equation 1:

k_{ls} is the load sharing factor.

The resistance side of equation 2 can be written in the form of a design code equation as:

$$f_{m;0;d} = k_{ls} \frac{f_{m;0;c} \, k_{\mathrm{mod}}}{\gamma_M} \qquad (3)$$

in which:

$f_{m;0;d}$	is the design bending strength;
$f_{m;0;c}$	is the characteristic 5th percentile bending strength;
k_{mod}	is the modification factor for duration of load and service class;
k_{ls}	is the load sharing factor.

The value of k_{ls} depends on, among others [Rackwitz, 1992],:

- the ratio of load variability against the variability of the system resistance;
- the variation in material properties within the species and/or the grade;
- the amount of plasticity which can occur in the failing stage of a board;
- the size of the board;

- the topological arrangement of the structural members (tongue and groove);
- the dependence structure of the resisting variables.

The value of k_{ls} currently specified by Eurocode 5 is 1.1.

3 EXPERIMENTAL PROGRAMME

3.1 Introduction

The experimental programme consisted of a series of tests on single boards as well as a number of tests on full scale sheet pile walls consisting of five parallel boards.

3.2 Material properties of boards

The material properties of azobé and pine have been determined in flatwise bending tests of boards with tongue and groove profile. Because of the specific application in sheet pile walls the length to thickness ratio of the specimens was 90 for azobé and 67.5 for pine. The test length was 5400 mm. All specimens were tested with a moisture content above the fibre saturation point and deflection was measured until failure occurred. Load-deflection diagrams allowed for the determination of plasticity which occurred in the boards. The term plasticity is used for plastic failure in the compression zone but also for the sometimes occurring slow crack growth in the tension zone of individual boards.

In addition to the plasticity measurements and the bending strength, the dynamic modulus of elasticity was determined using longitudinal vibration measurements with the Grindo-Sonic machine and the static modulus of elasticity (MoE) was determined in deflection tests. These measurements were used to determine regression equations to predict the strength of boards which would later in the study be tested as a part of a full size sheet pile wall. It was found that in the case of pine the best strength predictive parameter was the static MoE, while in the case of azobé this was the dynamic MoE. It was found for both species that adding more parameters to the regression equation, (additional MoE value, density), could only slightly improve the prediction of the bending strength.

The boards were visually graded in accordance with the Dutch visual grading standards, i.e. NEN 5480 Quality Class A/B for azobé and NEN 5466 Quality Class C or better for pine.

A typical test result showing the amount of plasticity which may occur in a wet board is shown in figure 2.
In figure 3 a typical failure pattern of an azobé board is shown. The material properties of the two species are gathered in table 1. The coefficients of variation (CoV) are also given.

3.2 Full size tests

A special test set-up was developed in order to be able to obtain large deflections, and also to allow for differential deflection over the width of the wall. Details of the test set-up are given in [Van de Kuilen et al., 1996]. A picture of the possible movement of the supports as a result of the large deflections is shown in figure 4.

In figure 5 a photograph is shown of a sheet pile wall in the test setup. 10 sheet pile walls were tested for azobé and pine respectively. Some of the sheet pile walls were 'designed' to be especially weak, strong or stiff. This specific design was made based on the non-destructively determined parameters such as dynamic and static MoE and density. These ‘specific’ walls were used to validate the computer model.

The results of the full size tests were used to determine the experimental load sharing factor. The experimental load sharing factor was defined as the characteristic value of the bending strength of the sheet pile wall, divided by the characteristic strength as obtained from the analysis of the results of the individual boards.

The determination of the characteristic bending strength of the sheet pile walls was carried out such, that the specific sheet pile walls with 'extreme' values were neglected from the analysis. Otherwise the extremely designed sheet pile walls would influence the characteristic value too much. The experimental load sharing factors derived were 1.17 for azobé and 1.32 for pine.

4. NUMERICAL MODELLING

A numerical model was developed using a combination of Monte Carlo simulation with a finite element model of a sheet pile wall. The finite element code DIANA was used for the calculations. A finite element model was created with 3, 5, 10 or 20 boards in parallel. Each individual board was then assigned a set of material properties, consisting of compression and tension strength as well as a cracking criterion. Modelling of the failure behaviour also included plasticity and softening, in order to properly model the plastic behaviour observed in the bending tests. It was found that for uniaxial stress states the Hoffman yield criterion in combination with a crack criterion can be used. The Hoffman yield criterion, however,canonly be used for timber assuming that the compression and tensile strengths are equal in the directions perpendicular to the grain. With this assumption it will be possible to model different compression and tension strength values in the direction parallel to the grain. In all other cases the Hoffman yield criterion will overestimate the uniaxial strengths in another direction and cannot be used in timber design [Van de Kuilen, Van der Linden, 1994]. The assignment of material properties (strength and stiffness values) was carried out on the basis of the regression equations derived from the test results of the single boards of the two species. A ratio of 1.8 between tension and compression strength best described the test results, which is not uncommon for wet timber with small depths [Van der Put, 1993].

The results of the numerical model were verified with the full scale tests. This was done by calculating the strengths of the tested walls. The average deviation between the calculated result and the test result was about -2.7% in the case of pine and +1.3% in the case of azobé. Maximum deviations were -14% to +6% in the case of pine and -5% and +6% for azobé for the most extreme sheet pile walls that were assembled. Consequently, it was concluded that the numerical model was accurate enough to calculate the ultimate load carrying capacity of timber sheet pile walls.

5. MONTE CARLO SIMULATIONS

Monte carlo simulations were carried out on sheet pile walls with 3, 5, 10 and 20 boards in parallel respectively. In each case 100 walls were calculated. The influence of the number of parallel boards was large when the number of boards increased from 3 to 5, but an increase from 5 to 20 did not show an improvement in load sharing anymore.

The results of the Monte Carlo simulations indicated a large effect on the fifth percentile value of the strength distribution of the load carrying capacity of the sheet pile wall. This influence is shown in figure 5. The load carrying capacity of azobé boards is shown with 3, 5 and 10 boards in parallel. The load sharing factor was determined to be 1.10 for 3 parallel azobé boards and 1.19 for 5 or more boards. For pine these values were determined at 1.21 and 1.34 respectively. Other span/depth ratios showed the same increases.

6. CONCLUSIONS

Load sharing effects were studied in timber sheet pile walls using a combination of full size tests and numerical modelling. A considerable higher load-sharing factor was found than the one currently specified in Eurocode 5. This is caused by the fact that wet timber has a better plastic capacity than dry timber, which is used in most structures. Provisions for the applicability of the load sharing factors are that the grade of the timber complies with the regulations, i.e. for azobé in accordance with NEN 5480 Class A/B and for pine in accordance with NEN 5466 Class C or better.
The numerically and experimentally found load sharing factors were close to each other. Based on the results of both the experiments and the Monte Carlo simulations a value of 1.17 for azobé and 1.33 for pine can be used for engineered timber sheet pile walls.

7. REFERENCES

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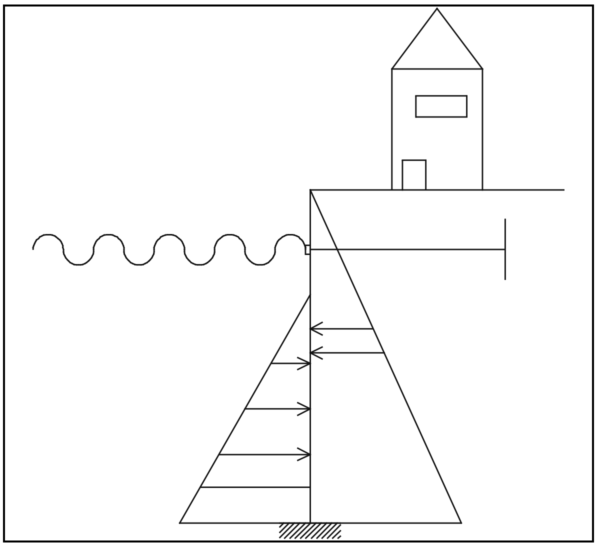

***Figure 1**. Principle of sheet pile wall with anchor wall.*

Species:	MoE-stat (N/mm^2)	CoV	MoE-dyn (N/mm^2)	CoV	MoR (N/mm^2)	CoV	ρ_{wet} (kg/m^3)	CoV
Azobé	16,300	12%	17,500	11%	78.5	16%	1130	8%
Treated pine	9,300	18%	10,500	18%	30.1	22%	720	13%

Table 1. Material properties of single boards.

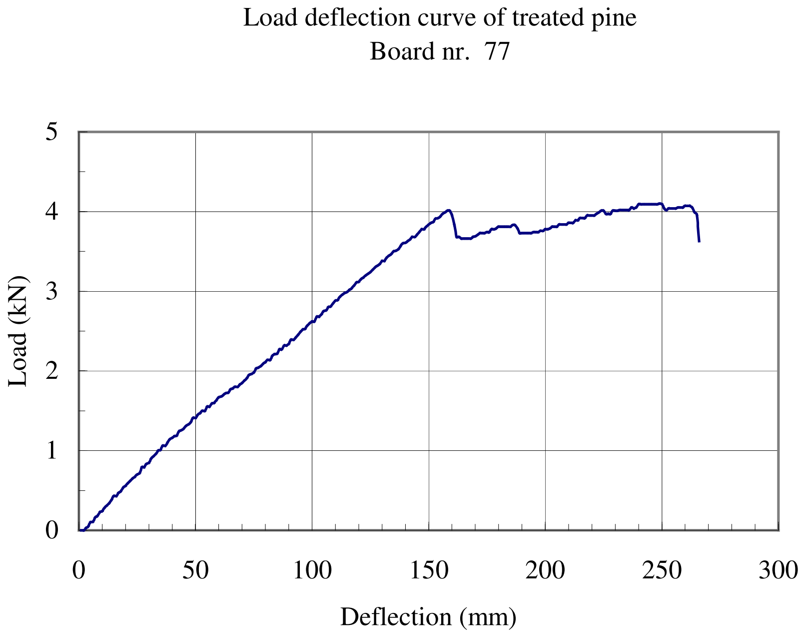

***Figure 2** - Test result of a board showing the amount of plasticity.*

Figure 3 *- Typical failure pattern of azobé boards.*

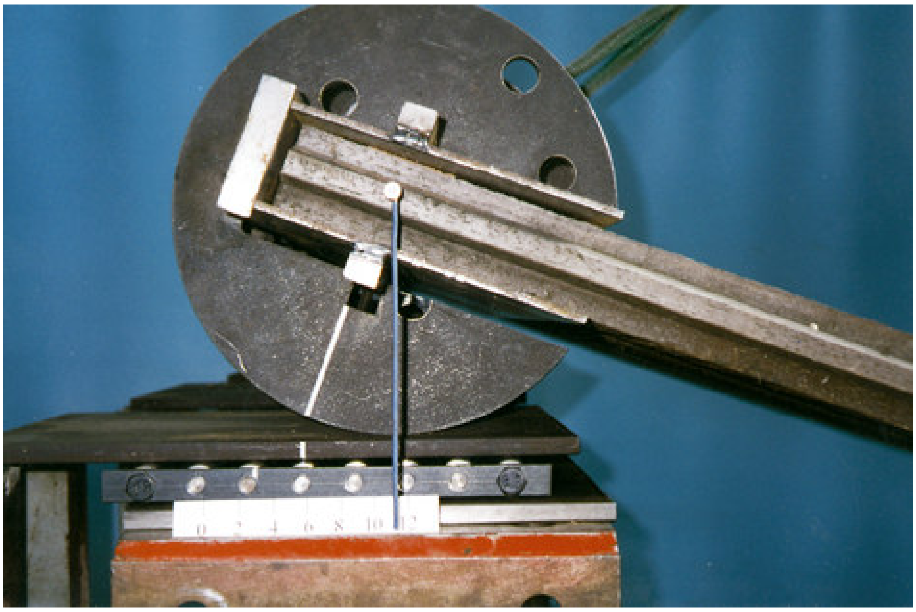

Figure 4 *- Horizontal displacements of the supports at large deflections.*

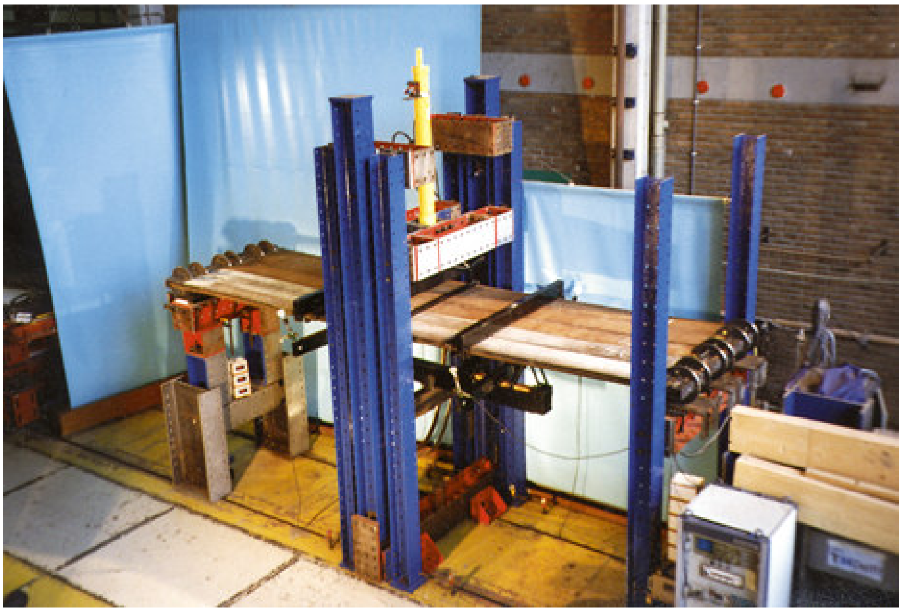

Figure 5 - *Test set-up with sheet pile wall of five parallel boards.*