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# A timber guardrail for highways made with hardwoods

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## ABSTRACT

*A timber guardrail made of sustainable tropical hardwoods has been developed in the Netherlands. The guardrail is an environmentally friendly alternative for zinc-coated steel barriers. The guardrail is made of a combination of two durable hardwood species: angelim vermelho (Dinizia excelsa) from Brazil and azobé (Lophira alata) from Africa. Full-scale tests have shown that the guardrail is able to withstand the impact of a 13000 kg bus driving at a speed of 70 km/h and an impact angle of 20 ° as well as that of a car of 900 kg having an impact speed of 100 km/h and same angle. Steam bent curved boards are used as energy absorbers from the passenger car impact. After the full-scale tests with the bus, no damage was found in the timber elements, and the guardrail had only to be straightened, saving repair costs during the service life of a guardrail. The guardrail fulfils the requirements specified in European standard EN 1317 Road Safety Systems for the H2 level with accident severity index of 1.0.*

## 1. INTRODUCTION

The In the Netherlands a wooden guardrail for highways has been developed with the shape of a tulip. The development was initiated due to concerns of zinc pollution caused by steel guardrails and the environmental impact in general of steel. The hot-dipped galvanised steel guardrails have a zinc layer to protect them against corrosion. However, this layer slowly leaches into the environment during the working life and an estimated 3000 tons of zinc leaches to the environment each year in Europe because of this. In the development to a more sustainable society, an alternative for the steel and concrete guardrails has been developed. Although timber guardrails already exist in a number of countries, they are either not suitable for highways or made of a combination of steel and timber. Europe has more than 75000 km of motorways based on 2017 data according to Eurostat. With an approximate lifetime of 20 years for a guardrail, the market potential for an environmentally friendly alternative is large. The timber alternative has been developed in a project sponsored by the Dutch Road Authority, the Dutch Timber Information Centre and Delft University of Technology.

## 2. REQUIREMENTS FOR THE NEW GUARDRAIL

In conjunction with the highway authority, a list of requirements was generated that should be fulfilled. A distinction was made between requirements specifically dealing with guardrails and other, more general requirements. In Europe the safety level of guardrails is regulated in standard: EN 1317-1 - Terminology and general criteria for test methods, and EN 1317-2 – Performance classes, impact test acceptance criteria and test methods. The three main criteria that define the capabilities of a safety barrier are the containment level, the impact severity and the deformation of the restraint system. The containment level represents the capacity of the guardrail to withstand vehicle impacts. The standard specifies the characteristics of the tests, in terms of vehicle impact speed, impact angle and vehicle mass. The requirements for Dutch highways are for a H2 containment level and are given in Table 1.

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Table 1: Requirements for a guardrail at H2 Level

| Test | Speed (km/h) | Angle (°) | Mass (kg) | Vehicle |
|---|---|---|---|---|
| TB 11 | 100 | 20 | 900 | Car |
| TB 51 | 70 | 20 | 13000 | Bus |

The standard gives three impact severity levels A, B and C as a function of the Acceleration Severity Index (ASI value). This value, derived from accelerometers mounted inside the test car, should preferably be not more than 1.0, (level A) but definitely not more than 1.4 (level B) or 2.0 (Level C). When the requirements for Level A are fulfilled, the possibility of passengers surviving the crash is good and is the preferred level.

During a collision, no elements may be loosened from the main guardrail, thus endangering other people or traffic, nor may structural parts penetrate into the passenger compartment of the vehicle.

Additional requirements are:
- Animals have to be able to trespass the guardrail without problems.
- The environmental impact has to be less than that of an equivalent steel guardrail.
- 'cladding' of steel elements with timber is not allowed, and at least 60% of the guardrail has to be made of structural timber.
- The life-cycle costs of the timber guardrail shall not exceed those of an equivalent steel guardrail. The cost in mass production may be maximally 20% higher.
- The design has to be recognizable as timber guardrail and be innovative.

The objective regarding the performance of the guardrail was ranked top priority, as the highway authority wanted to demonstrate the feasibility of timber as a modern construction material. The development of the guardrail was divided in a number of stages, starting with information analysis, conceptual design, crash simulations and engineering and finally a number of prototype and full-scale tests.

### 2.1. *INFORMATION ANALYSIS*

The requirements were discussed and analysed in close cooperation with the highway authority. A patent search was performed to find existing systems and technologies that could serve as a basis. Some patents came up on a timber guardrail, consisting a combination of roundwood and steel plates, but approved for secondary roads only.

The functional performance of the current types of guardrail were also thoroughly analysed and experiences from the highway authority were discussed in-depth. This cooperation was maintained throughout the project to receive feedback on the design but also to increase the acceptance level of a timber guardrail as a viable product. It was concluded that a new working concept was needed for the timber guardrail to be able to fully utilize the material properties of timber.

### 2.2. *CONCEPTUAL DESIGN*

The first step in the development stage consisted in the use of creative technologies to generate concepts for guardrails. Brainstorm sessions and technical discussions with experts resulted in about 200 designs. Together with the highway authority, this was then brought down to 4 viable concepts, each having about 7 alternatives.

In the end, the highway authority decided that the “Tulip” design concept should be developed into a prototype. An artist impression of the tulip and some alternatives are shown in figure 1 and 2. The Tulip was valued as most innovative and was chosen for further development, accepting that the design involved some more ´unkown´ parameters with respect to performance and manufacturing, as well as expected final costs.

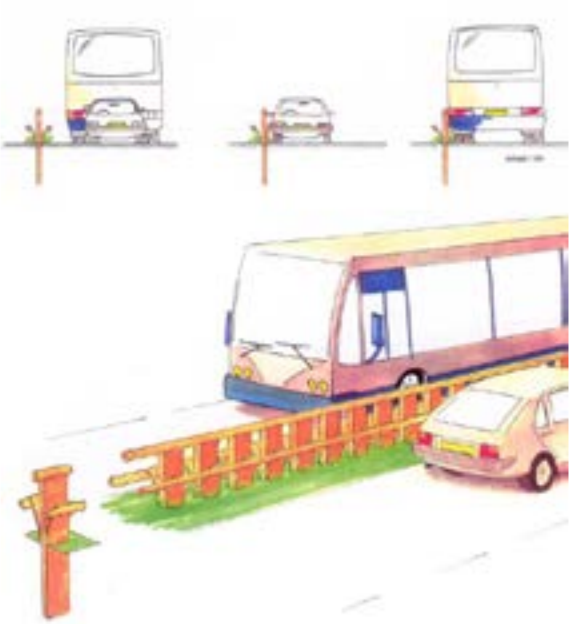

Figure 1: Chosen design for further development.

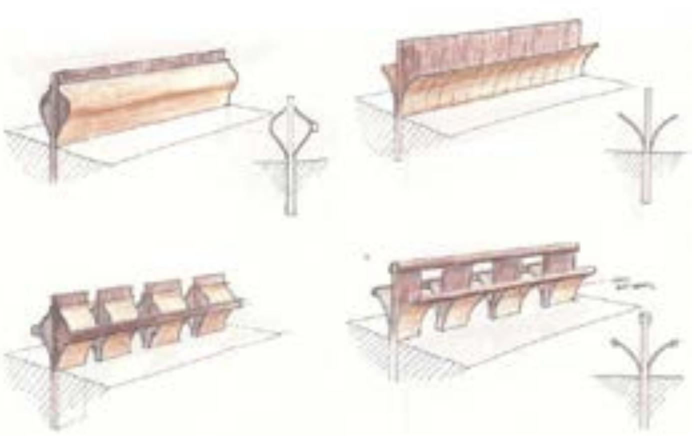

Figure 2: Design alternatives with steam bent timber.

## 3. STEAM BENT TIMBER

The guardrail has a small steam bent timber 'leaf' allowing small cars with occupants to be decelerated within acceptable levels (ASI-value) and a larger double beam 'flower', supported by posts, to withstand a bus impact. Steam bent timber elements were expected to have good energy dissipating behaviour, but no quantitative data was available. The steam bent leaf is curved into a specific shape that allows for energy dissipation without the timber splintering or loosening from the rail during impact. Consequently, a series of tests were carried out on small clear specimens sawn from new boards, on steam bent boards, as well as boards that were steam bent and then straightened again in a reverse process. Compression tests were carried out on small clear specimens of Angelim Vermelho and French Oak with sizes 20 x 20 x 60 mm and tension tests were carried out on 20 x 20 x 200 mm. The boards were carefully selected at the sawmill and could be considered defect free. The same quality of boards should be used in the actual guardrail, since boards with defects cannot be bent properly without cracking of the convex face or compression (buckling) failures of the concave face [Stevens and Turner, 1970]. The wood fibres that are ‘crushed’ during the bending process with steam can be straightened again without breakage of the fibres and without cracking the elements. Only when the board is curved in the opposite direction, failure (cracking) will occur.

The typical stress-strain diagram for Angelim Vermelho as calculated by Abaqus on a reference block with a compression strength of about 58 MPa and a tensile strength of around 60 MPa is shown in figure 3. The stiffness difference between compression and tension is noticeable, as well as the large non-linear deformation capacity in compression. Furthermore, in tensile the material behaves brittle with a slight non-linearity.

The prototype of the joint between the post and the steam bent elements was designed with two steel bolts M16. The white nylon spacer between post and board is 20 mm thick and allows for a larger stroke, giving more energy absorption, but also allows water and dirt to run through in the final application, increasing the durability of the system. In order to be able to calculate the stresses in the steam bent timber, a new non-linear material model was developed and implemented in the Finite Element Code Abaqus [Pronk et al. 2002].

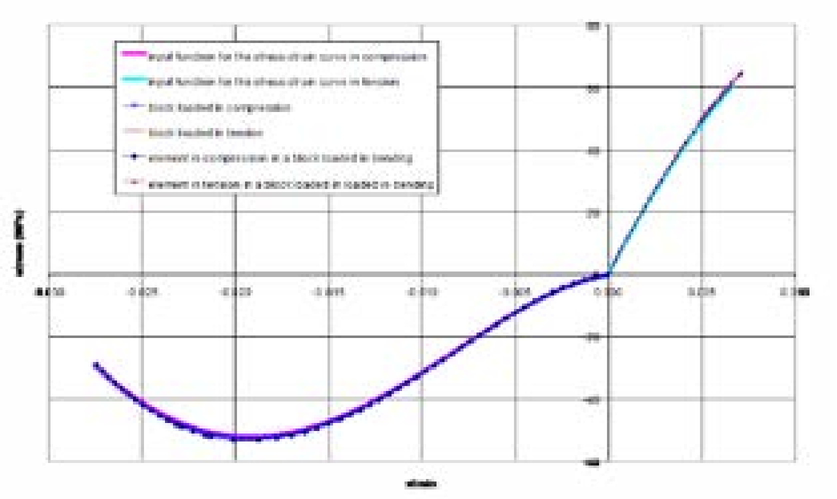

Figure 3. Stress-strain diagram of steam-bent timber for the guardrail simulations

After the preliminary material testing of the steam bent timber, a prototype was built to investigate the behavior of the system ´pile – connection – leaf – car rail´. The system was not tested under impact, but under quasi-static loading. The goal was twofold. On the one hand, the energy dissipation needed to be determined, and secondly, the robustness of the system needed to be verified, as no cracks of failures were supposed to happen in a crash situation. The behavior of the system under loading (rotated under 90° with respect to the application) is shown in figure 4.

Figure 4. Three stages of bending of the steam bent element with car rail, connected to the pile with two bolts and white coloured spacers.

From figure 5, the large energy dissipation capacity of the system can be seen, as the surface under the curve is quite large. In future work, the dynamic impact behavior of the system could be evaluated in more depth, as it remains uncertain if the energy dissipation under impact loading is the same as under quasi-static loading. The quasi-static loading values were used in the subsequent simulations, that showed to be pretty accurate when compared to the actual test results from the full scale tests.

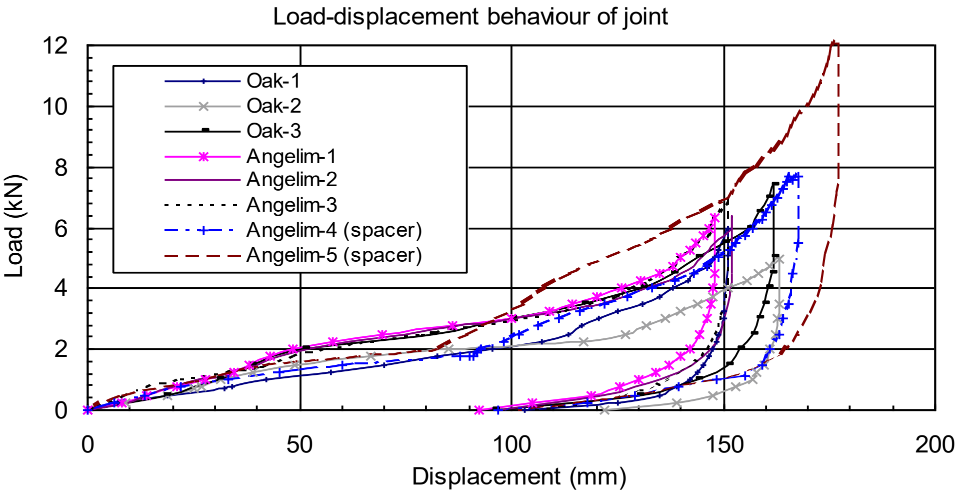

Figure 5. Load-displacement relationship of the car rail connected to the pile.

## 4. CRASH SIMULATIONS AND ENGINEERING

### *4.1. INTRODUCTION*

After the selection of the "Tulip" design concept, an inventory was made of the design parameters that would determine the sizes and shapes of the prototype components. The Tulip consists of a short pile in the ground (post), a top rail (bus rail), a small 'leaf' of steam bent timber (car board) connected to the post just above ground level and a small rail (car rail) that are connected to the piles through the car boards. These elements were modelled in a Multi-Body analysis program (MADYMO®) and a parameter study was performed. Crash simulations performed with this program give an indication of the necessary strength/size ratios for the different elements with output of system deformations, but also ASI-values. The elements and joints that were analysed in the simulations and are given in Table 2. The choice of wood species was postponed as long as possible to ensure freedom in design and manufacturing. Instead of selecting a wood species, the optimisation of the design was performed with the parameters strength/stiffness and natural durability/structural detailing measures, but also in contact with industry concerning manufacturing and wood availability.

Table 2. Parameters to be analysed in the crash simulations

| Parameter: | Mechanical property | Axes | Remark |
|---|---|---|---|
| Depth of post | Soil strength/stiffness | x, y, z | laboratory research required |
| Size of post | Bending strength/stiffness | x, y, z | includes torsion and spacing |
| Joint post – bus rail | Strength/stiffness | x, y, z | - |
| Size of bus rail | Bending strength/stiffness axial strength/stiffness | x, y, z | - |
| Joint post - car board | Rotational stiffness | x | laboratory research required |
| Size of car board | Bending strength/stiffness | x, y, z | includes torsion and spacing |
| Joint car board – car rail | Strength/stiffness | x, y, z | - |
| Size of car rail | Bending strength stiffness, axial strength /stiffness | x, y, z | includes torsion |

Apart from the timber components, the longitudinal joints for the car rail and the bus rail were designed and analysed. The crash simulations predicted the loads on these joints and an increased strength for loading periods lasting not more 30 milliseconds [Bocchio et al., 2001] was taken into account.

During the engineering phase, laboratory tests were performed on two components of the Tulip: the post in the ground and the car board (steam bent timber). A static calculation had shown that the post should be placed at 1-meter depth, but the reaction forces could only roughly be estimated. Therefore, a steel tank was filled with sand usually used in roads. Then a post was placed in the ground and a sway mass was used to determine impact forces and moment-rotation behaviour, both parallel and perpendicular to the traffic direction.

After the laboratory tests, additional Multi-Body analyses were performed that included the test results. The final required dimensions of the elements were determined, and the vehicle behaviour was analysed for stability and re-entry behaviour. For the bus, the strength and integrity of the system is important. The impact of a 13.000 kg bus was a challenge to master but after a number of changes in parameters it was found that a bus rail from Strength Class D60 in accordance with European strength class standard EN 338 should be able to perform well under these conditions. A lower strength class combined with larger dimensions of this element was felt to change the design too much. The post could be made of a lower strength class and alternatives for the post are possible by varying the spacing and/or the thickness. In figure 6 some timesteps from for a car and a bus simulation are given. After these calculations and simulations, the technical drawings were prepared for the prototype.

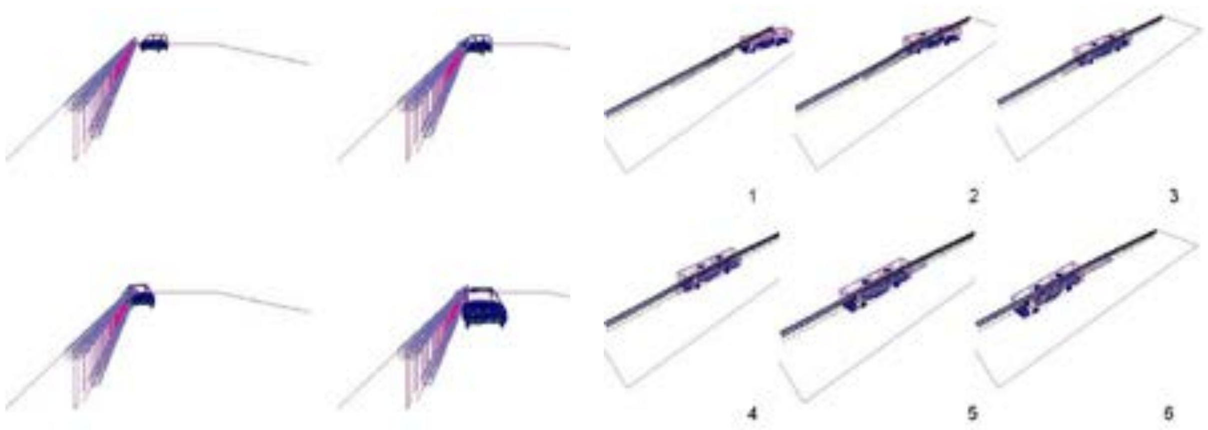

Figure 6. Simulation images for car (left) and bus (right)

### *4.2. SIMULATION RESULTS AND PROTOTYPE BUILDING*

After the numerical simulations the design was finalised and technical drawings were made for a prototype. An unexpected results from the simulations was that, besides transversal forces also large vertical (upwards) forces needed to be taken into account, especially for the bus crash. These forces cause double bending in the rail, increasing the required sizes considerably. In addition, the vertical forces have to be transferred to the piles, for which considerable diameter bolts are needed (about M20). Considering end and side distances and minimum spacings, this resulted in a bus rail consisting of two half circles with a radius of 150 mm. Since these dimensions were not available in angelim vermelho it was decided to make these rails of azobé (*Lophira alata*), which is a tropical species from Africa with comparable mechanical characteristics. The prototype is shown in Figure 6. The prototype was tested using large bags filled with a sand-filled plywood box. Tests were done on the car rail with an equivalent speed and energy as the transverse component of a car impact. For the bus, the speed of the sandbag was higher, but since the mass of the

Figure 7. 18-meter prototype of guardrail and sandbag test

sandbag was about one-tenth of that of a bus, the total impact energy of this test was about 25% of that of the transverse component of a bus. The main conclusion of these tests was that the prototype seemed to be robust enough. After this test, some slight alterations were made to the connections, mainly for aesthetic reasons. It was decided to replace 20 mm bolts by 20 mm threaded rods, to be mounted from the backside of the rail.

## 5. FULL SCALE TESTING

For the full-scale tests a guardrail of 80 meters in length was installed at the Test Centre Lelystad of the Dutch Vehicle Technology Information Centre RDW. A total of 4 crash tests were performed, one of which failed as the impact angle during the first bus test did not comply with the requirements. Firstly, a car crash test was performed in accordance with EN 1317. The car used was a Peugeot 205. The impact speed of the car was 100.3 km/h and the impact angle 20°. Although roll behaviour and re-entry angle fulfilled the requirements as specified, the ASI-value was determined at 1.46 or 4% above the limit of 1.4 as specified in the standard. Consequently, the guardrail has not passed the test and modifications are necessary before approval can be obtained. The difference between the simulated ASI value and the actual ASI value is thought to be caused for a great part by the difference in soil behaviour between the laboratory test and the soil behaviour on the test site. On the test site, in fact, a combination of saturated clay and sand is present, while sand was used in the laboratory test. A sensitivity study showed that under these conditions the simulated ASI value could have been 1.3. Another reason for the higher ASI value is the high friction between car and guardrail in the full-scale test. After having examined the damages on the guardrail and the analysis of the test data, it appeared that the friction had caused an increase in the longitudinal acceleration. As a second bus test had to be performed, this gave the opportunity for an improved version of the car rail to be tested. A top view from four stages of this test is shown in Figure 8. The new car rail was optimized for more energy dissipation and an ASI-Value of 1.0 could be achieved, classifying the rail in the best class for small cars.

Figure 8. Top view with a high speed camera of the car impact on the guardrail, Full-scale test with a 900 kg car (Test TB 11 according to EN 1317)

The second bus test was successful, whereas the first bus test did not go according to protocol. After the towing truck released the bus, the vehicle deviated from the intended track, and the impact angle became 26° instead of 20°. As a result, the kinetic impact energy was $\sin^2(26)/\sin^2(20) = 1.64$ times the intended impact energy. The speed of the impact was estimated to be between 65 and 70 km/h. Although the bus did not crash through the barrier, the primary rail broke and this is not allowed according to EN 1317. However, with the results from the first test, the second prototype A sequence of high-speed camera photographs of the backside of the bus is shown in figure 8. After the test, the guardrail is inspected for failures. No cracks or other damage occurred to the posts or the bus rail. The guardrail only has to be straightened, saving repair costs and traffic lane closures.

Figure 8. Back view from a full-scale test with a bus. No damage to the timber, except a need for straightening, saving repair time and costs.

## 6. SUMMARY

A timber guardrail for highways has been developed and successfully tested. After laboratory test on small elements and a many crash simulations, full-scale tests have shown that the guardrail fulfils all the requirements as specified in EN 1317 for both a car and a bus. The ASI-value was determined at 1.0, which is just within Class A. After impact, only minor repairs are necessary, saving time and money on traffic lane closures. The guardrail is ready for application along European roads for a H2 containment level in accordance with EN 1317.

## ACKNOWLEDGEMENTS

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## REFERENCES

*ABAQUS User manual, Hibbitt, Karlsson & Sorensen, Inc., 2001*

*Bocchio, N., Van de Kuilen, J.W.G., Ronca. P. Impact loading tests on timber beams, IABSE Conference on Innovative Wooden Structures and Bridges, Lahti, Finland, 2001*

*EN 1317. Roadside Safety Systems*

MADYMO 5.4, TNO Road-Vehicles Research Institute, The Netherlands.

*Pronk,M., Van de Kuilen, J.W.G., Antonelli, V., An advanced non-linear material model for timber, 7th World Conference on Timber Engineering, WCTE 2002, Shah Alam, Malaysia*

*Stevens, T.C., Turner, N, Wood Bending Handbook, 1970.*

*Writing User Subroutines with ABAQUS, Hibbitt, Karlsson & Sorensen, Inc.*