Structural application of perforated aluminium plates in a footbridge canopy

Citation for published version (APA):
Hove, van, B. W. E. M., & Soetens, F. (2013). Structural application of perforated aluminium plates in a footbridge canopy. In V. Songmene (Ed.), *Proceedings of the 12th International Aluminium Conference (INALCO), 21-22 October 2013, Montreal* (pp. 72-81)

Document status and date:
Published: 01/01/2013

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 17. Nov. 2023

Structural Application of Perforated Aluminium Plates in a Footbridge Canopy

B.W.E.M. (Dianne) van Hove
b.w.e.m.v.hove@tue.nl
Eindhoven University of Technology
Faculty of Architecture, Building and Planning
Unit Structural Design
Eindhoven, The Netherlands

F. (Frans) Soetens
f.soetens@tue.nl
Eindhoven University of Technology
Faculty of Architecture, Building and Planning
Unit Structural Design
Eindhoven, The Netherlands

Abstract: A recently designed footbridge canopy covering a concrete bridge at the Eindhoven University of Technology campus is build up by aluminium plates containing perforations. The perforations differ in concentrations, diameter and pattern. The aluminium structure was adapted to improve global behaviour especially in relation with deformation requirements. Further experimental and numerical research was carried out to investigate the failure behaviour of perforated plates loaded by compression. It is concluded that the failure behaviour of relatively thin aluminium plates in compression is very complex, even for non-perforated plates (see [8]). Further fundamental research is needed to investigate failure modes and failure loads of the perforated plates.

Keywords: Aluminium canopy, perforated plates in compression, aluminium plates

INTRODUCTION

Within the context of the redesign of the Eindhoven University of Technology campus an existing concrete footbridge/cycling bridge spanning the river Dommel is planned to be upgraded into a temporary residence for students. The architectural design consists of an all aluminium canopy structure built up by perforated aluminium plates (see Fig. 1). Because the canopy is for temporary use only no further physical comfort conditions (f.e. thermal isolation) are required.

The material aluminium was chosen for its good corrosion resistance as well as its nice appearance in a green and quiet area. Further the perforations were chosen to enlighten the roofed area by natural light entering the structure through the perforations, which would make the bridge a pleasant and elegant place to stay. For the last reason the perforations should differ in concentrations, diameters and pattern.

Figure 1 Aluminium roof structure.

However, the architectural appearance was not yet worked out for structural requirements. Therefore design calculations were carried out on the overall structural behavior of the perforated canopy structure, finally leading to a better structural design fulfilling structural requirements on strength, stability and deformations (see [1]). Further detailed experimental and numerical research was carried out on the compressive behavior of perforated aluminium plates. This research was necessary because local and global stability of compressed perforated aluminium plates is not yet described in standard regulations, such as Eurocode 9 [2]. Of course the appearance of stress peaks plays an important role in the research.

ANALYSIS AND DESIGN ADAPTATIONS

At first the architect's design was worked out into a structural design globally calculated according to Eurocode 9 [2]. The aluminium alloy 5083-O was mainly chosen for its high ratio between characteristic tensile strength (270 N/mm^2) and 0.2% yield strength (125 N/mm^2) according to [2]. This could be a very important quality assuming high stress peaks near the perforations would not lead to rather brittle failure before extended deformations due to 'yielding' could take place. Besides this, the natural corrosion resistance of the 5083 alloy was very good as well.

The original cross sectional design [1] has been adapted due to extreme high deformations occurring for load combinations including snow. This load combination is supposed to be governing for ultimate limit state (ULS) as well as serviceability limit state (SLS), because the high snow load increases in the troughs of the roof, see fig. 2.

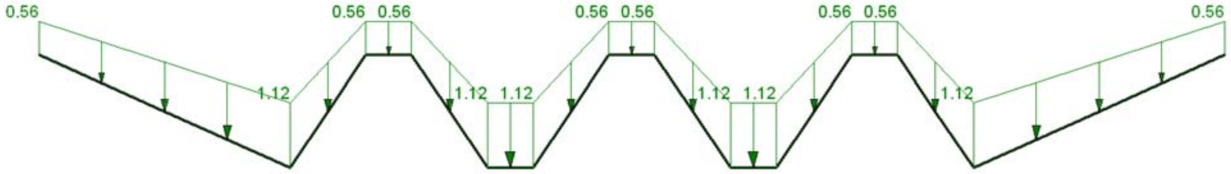


Figure 2 Snow loads in kN/m^2 on roof structure according to Eurocode 1 (see [3]).

Several design optimizations have been analysed, of which next three fit well to deformation requirements as well as construction limitation:

- Application of edge stiffeners by the formation of triangular plate girders, on the inside stiffened by ribs to better local buckling behavior (fig. 3);
- Application of cables on top of the roof spanning between the edge sections. Disadvantage was the relatively high load concentrations at cable fixation points (fig. 4);
- Application of plate stiffened ribs all over the structure (fig. 5). This structure was worked out further.

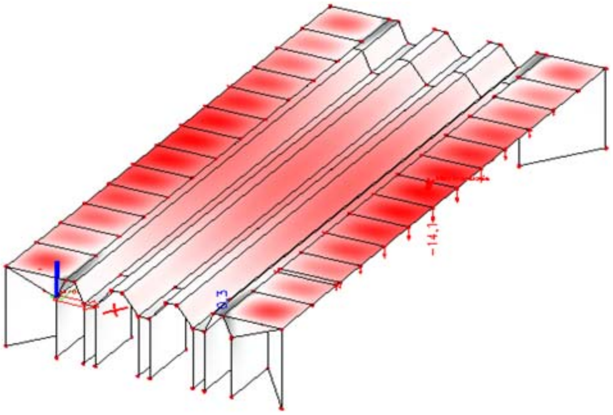


Figure 3 Structural design using triangular edge beams

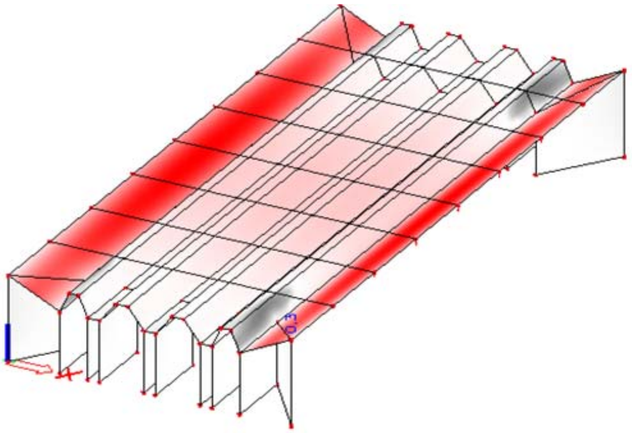


Figure 4 Structural design using cables

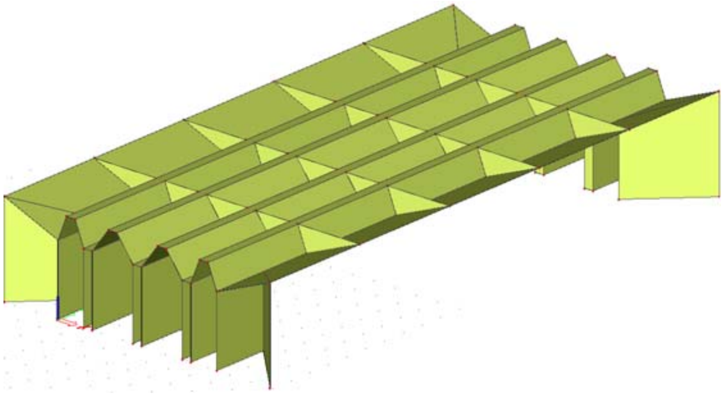


Figure 5 Structural design using plate stiffened rib

The best option (fig. 5) was calculated for SLS and ULS using ESA PrimaWin [3]. In a detailed study the structural design was further optimized for minimum costs by a reduction of the aluminium cross section (Fig. 6). The use of well designed plate stiffeners allowed the original plate thickness to be reduced from 10 mm to 4 mm, leading to weight reduction of the aluminium structure of half its original weight. Further, the design of rather simple extrusions connected by FSW has led to reductions of construction costs.

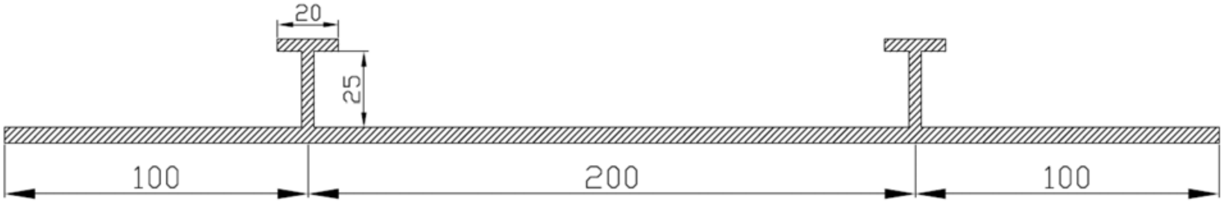


Figure 6 Optimized aluminium element [3]

The optimized design now fulfilled strength, stiffness and stability conditions according to Eurocodes 1 and 9. Besides this fabrication and construction could easily be carried out by the use of one die producing easy to handle and easy to connect extrusions (Fig. 6).

However, until so far calculations were carried out ignoring the influence of the perforation in the extrusions. Calculation and checks of perforated cross sections loaded by tension can be carried out according to design rules for tensile strength of cross sections in Eurocode 9 [2], supposing these design rules may be used for perforations with a diameter much higher than its plate thickness. Calculations and checks of perforated cross section loaded by compression is not included in national or international standards. For this reason numerical and experimental research on perforated plates load by compression was carried out.

NUMERICAL RESEARCH

Numerical research on perforated plates in compression has been carried out by Lelivelt [6] and Lenselink [7] using ANSYS for FEM analysis. Both researchers checked the numerical model on the analytical solution for load-deflection behaviour of non-perforated plates loaded by compression.

Numerical results of Lelivelt are summarized in Fig. 7 and 8 leading to the conclusion that for the investigated low perforation degrees (circa 10% of the cross section) the load reduction is not dependant on the diameter (which changed from 20 mm to 40 mm i.e. two to four times the plate thickness). The reduction compared to non-perforated plates was about 40 %.

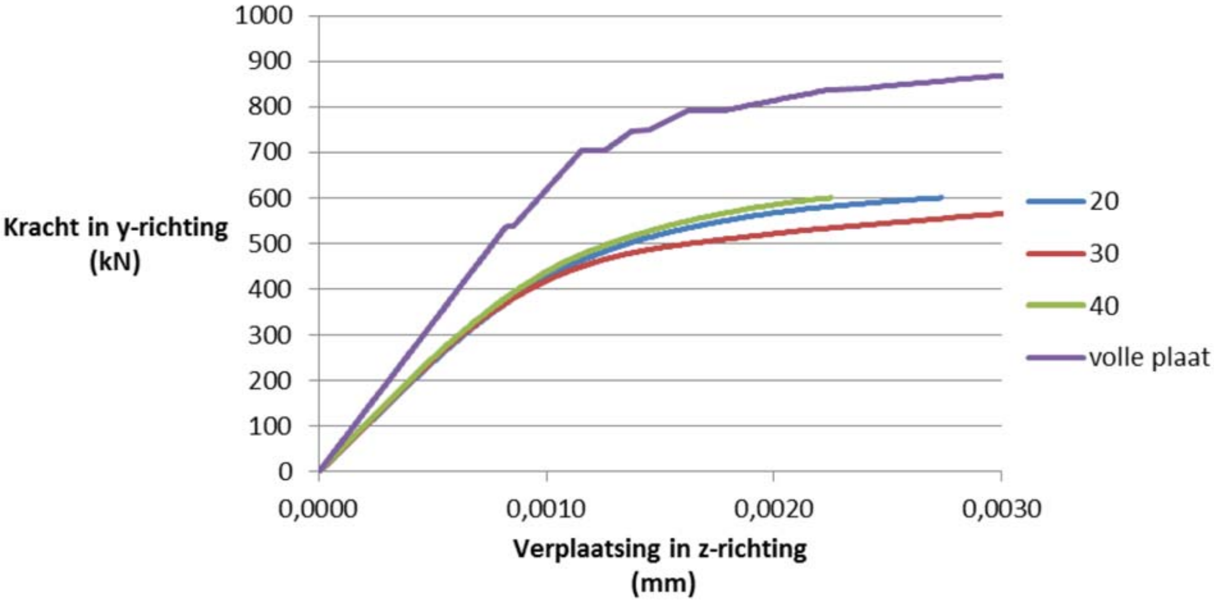


Figure 7 In plane plate loading versus out of plane deflections [6]

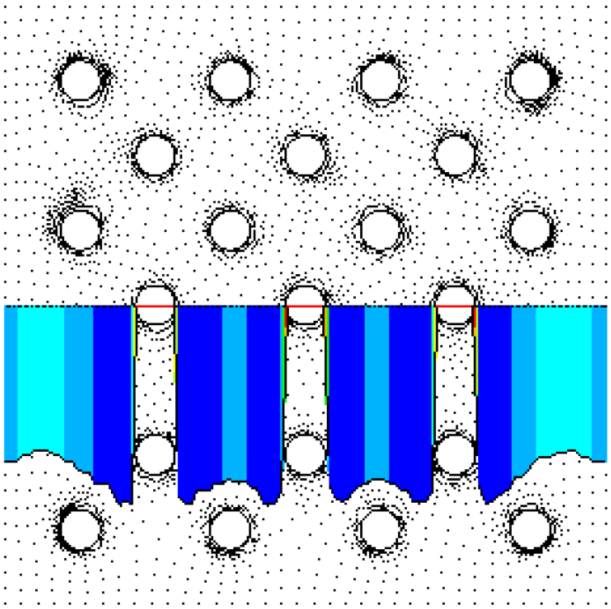
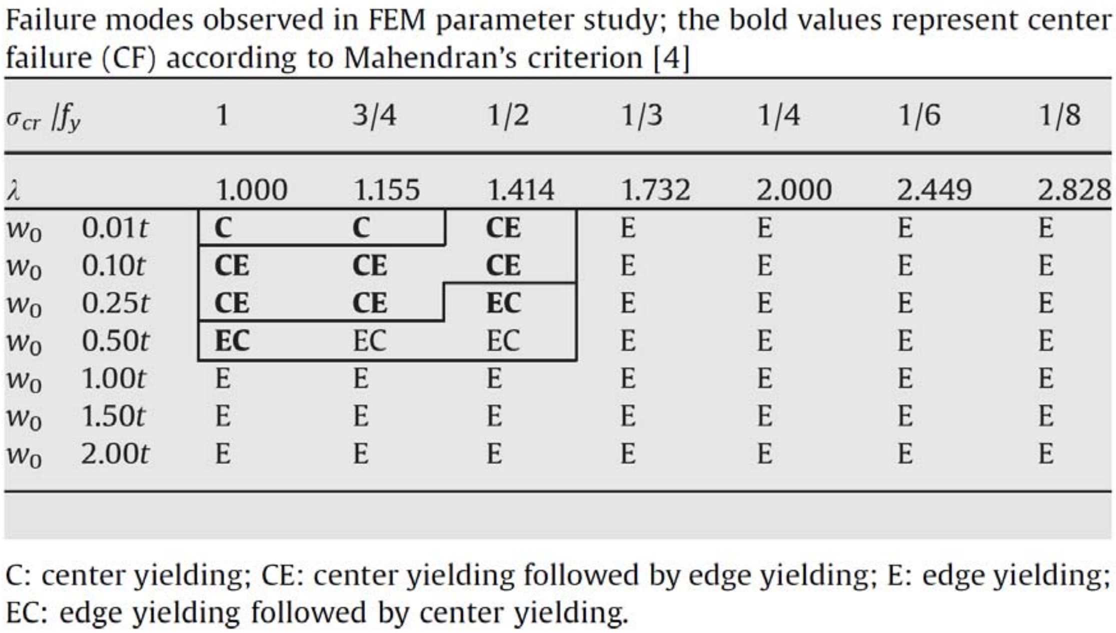


Figure 8 Load distribution and load concentrations at the midspan section

Results of numerical research recently started [7] on 300x300x10 mm plates and very slender 600x600x10 mm plates showed that local buckling is not always governing as was supposed in [6]. Fundamental analysis on plate buckling as described in [8] also showed that other failure modes may govern failure patterns, see Fig. 9. This research will be carried out further for the perforated plates as described in [6].



Failure modes observed in FEM parameter study; the bold values represent center failure (CF) according to Mahendran's criterion [4]

σ_{cr}/f_y		1	3/4	1/2	1/3	1/4	1/6	1/8
λ		1.000	1.155	1.414	1.732	2.000	2.449	2.828
w_0	$0.01t$	**C**	**C**	**CE**	E	E	E	E
w_0	$0.10t$	**CE**	**CE**	**CE**	E	E	E	E
w_0	$0.25t$	**CE**	**CE**	**EC**	E	E	E	E
w_0	$0.50t$	**EC**	EC	EC	E	E	E	E
w_0	$1.00t$	E	E	E	E	E	E	E
w_0	$1.50t$	E	E	E	E	E	E	E
w_0	$2.00t$	E	E	E	E	E	E	E

C: center yielding; CE: center yielding followed by edge yielding; E: edge yielding; EC: edge yielding followed by center yielding.

Figure 9 Table 2 in [8]

EXPERIMENTAL RESEARCH

Experimental research has been carried out on perforated 300x300x10 mm plates by Van Dun [4] and on perforated 400x400x10 mm plates by Chakiri [5]. Besides the difference in slenderness the experiments in [5] differed from the experiments in [4] in the execution of the boundary conditions in the test set-up as well as in the diameter and pattern of the perforation applied.

In the experiments described in [4] the perforation diameter varied between 20 mm (test serie B), 30 mm (test serie C)and 40 mm (test serie D). The perforations were spread over the plate as shown in Fig. 10. The quarter/half circles in perforations were not executed in the test specimen. The testing arrangement and its boundary conditions are shown in Fig. 11. The test results are shown in Fig. 12. It is clearly shown that the results for 10% perforated plates was more or less 400 kN, with no significant influence of the magnitude of the perforation diameter. The full strength (plates without perforation, test serie A) showed a mean strength of 550 kN. The main conclusion in [4], i.e. perforations decrease the ultimate limit strength with 25%, is only valid for the limited test series in [4], for not very slender plate (b/t = 30) and for the specific boundary conditions applied.

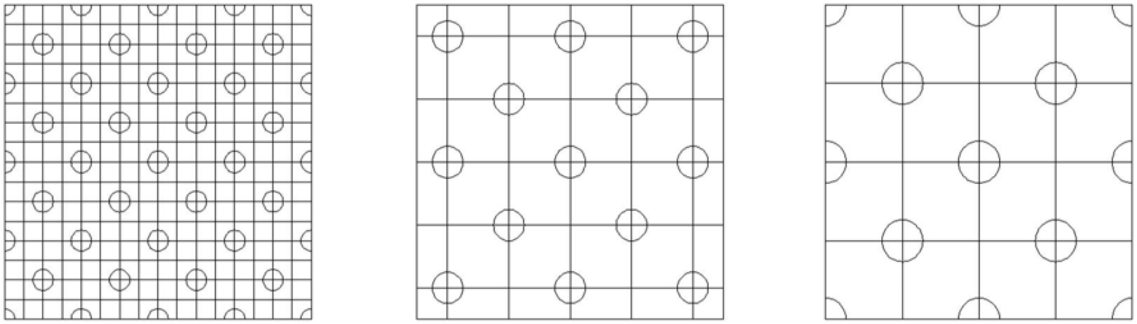


Figure 10 Perforation patterns in test specimen

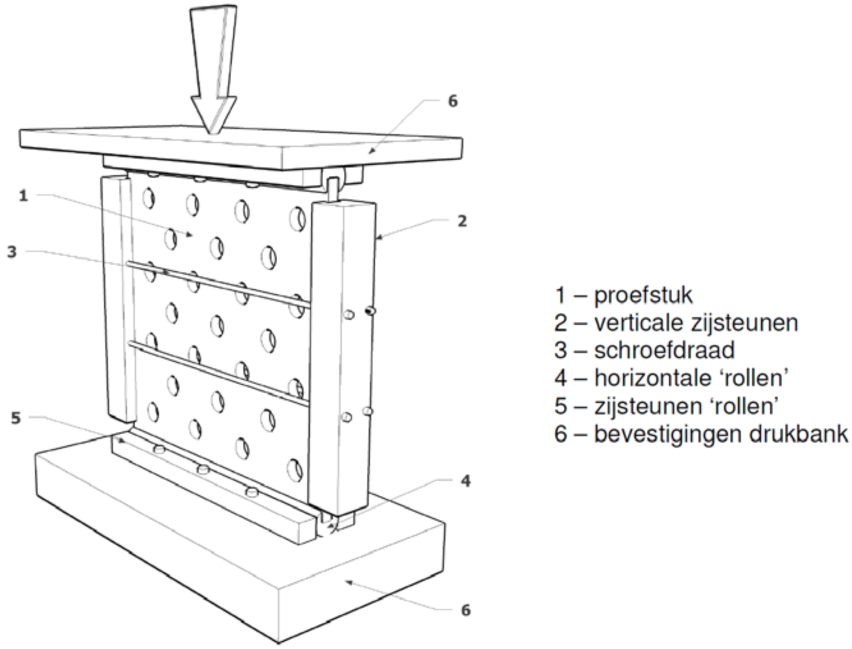


Figure 11 Testing arrangement

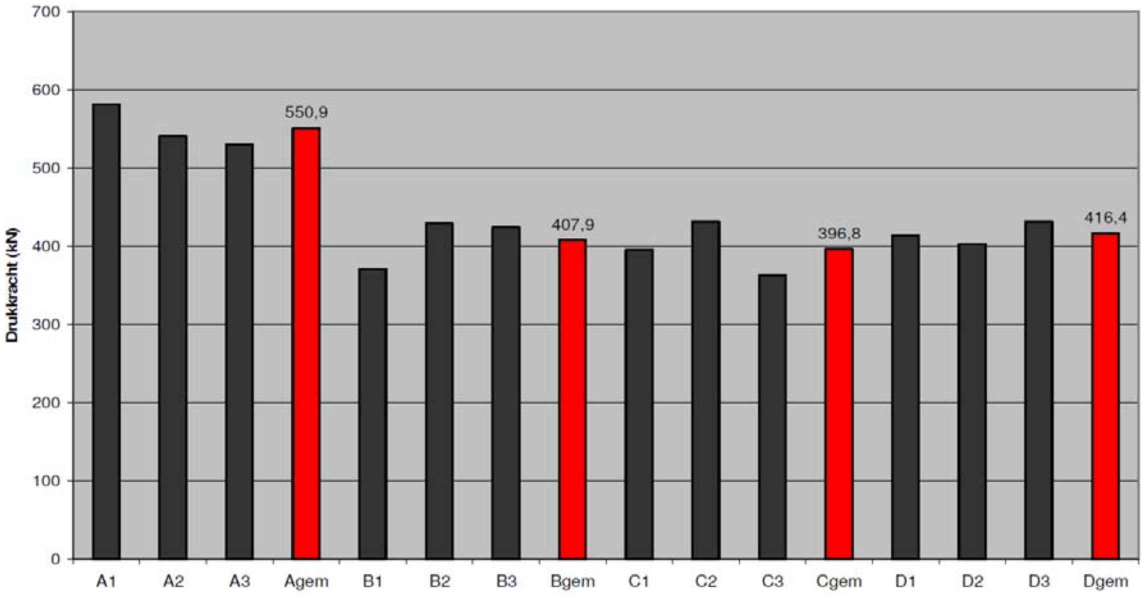
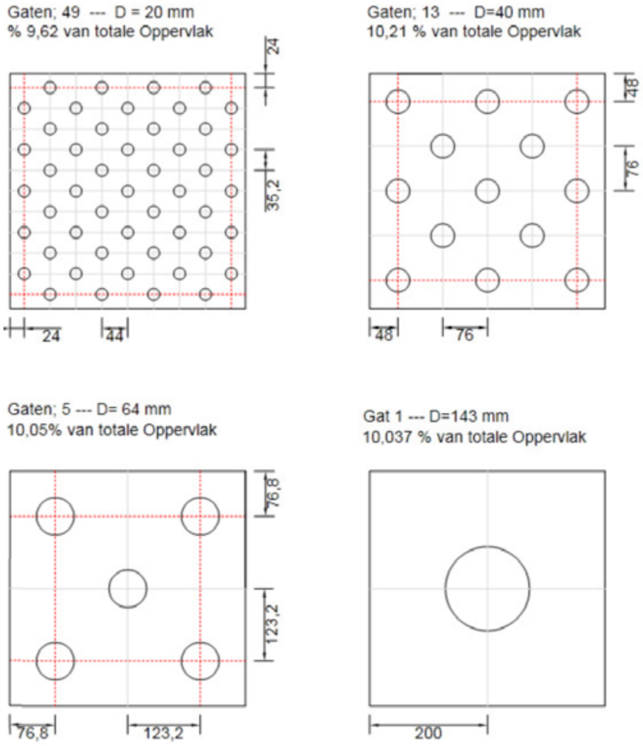


Figure 12 Compressions test results; average results in red.

In the experiments described in [4] the perforation diameter varied between 20, 40 64 and 143 mm, also leading to a perforation degree of 10%. The perforations were spread over the plate as shown in Fig. 13. The testing arrangement was in agreement with the arrangement used in [4], however its boundary conditions were changed as is shown in Fig. 14 and Fig. 15. The test results are shown in Fig. 16. Again it is shown that the results for 10% perforated plates was more or less the same for different perforation diameters; the overall mean value was about 380 kN. The full strength (plates without perforation) showed a mean strength of 503 kN leading to the conclusions that 10 % perforations decrease the ultimate limit strength with 25%, again only valid for the limited test series in [5], for medium slender plates (b/t = 40) and for the specific boundary conditions applied.



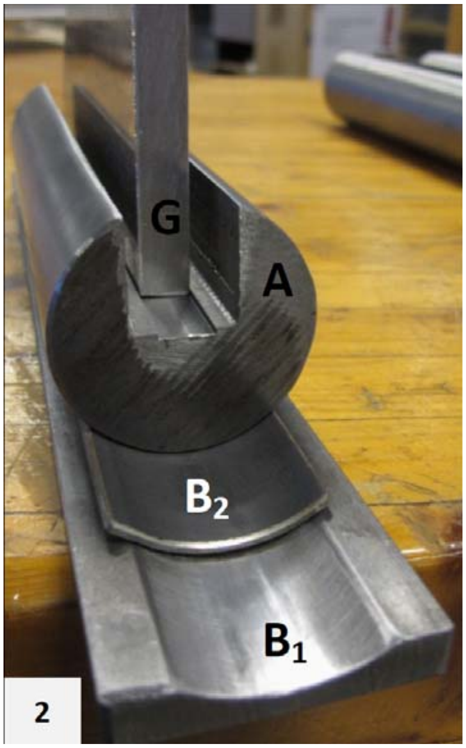


Figure 13 Perforation patterns in test specimen

Figure 14 Vertical support conditions

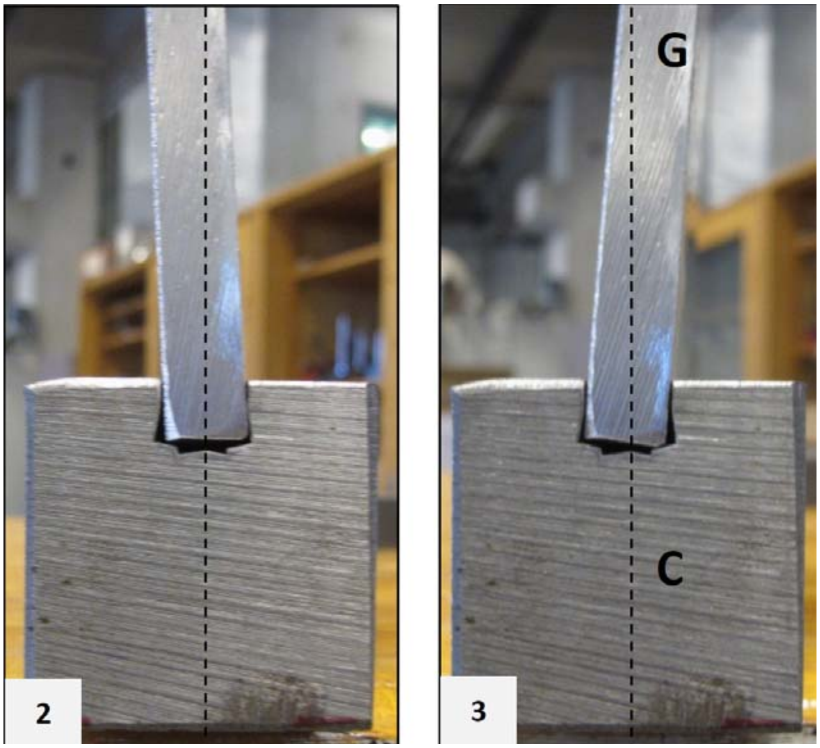
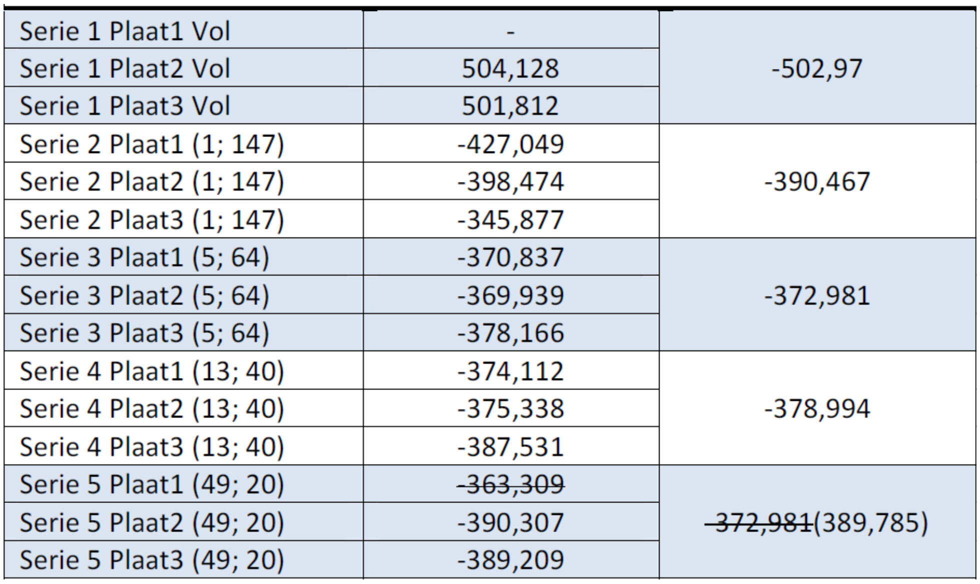


Figure 15 Horizontal support conditions



Serie 1 Plaat1 Vol	-	-502,97
Serie 1 Plaat2 Vol	504,128	
Serie 1 Plaat3 Vol	501,812	
Serie 2 Plaat1 (1; 147)	-427,049	-390,467
Serie 2 Plaat2 (1; 147)	-398,474	
Serie 2 Plaat3 (1; 147)	-345,877	
Serie 3 Plaat1 (5; 64)	-370,837	-372,981
Serie 3 Plaat2 (5; 64)	-369,939	
Serie 3 Plaat3 (5; 64)	-378,166	
Serie 4 Plaat1 (13; 40)	-374,112	-378,994
Serie 4 Plaat2 (13; 40)	-375,338	
Serie 4 Plaat3 (13; 40)	-387,531	
Serie 5 Plaat1 (49; 20)	~~-363,309~~	~~-372,981~~(389,785)
Serie 5 Plaat2 (49; 20)	-390,307	
Serie 5 Plaat3 (49; 20)	-389,209	

Figure 16 Compression test results (serial loads and mean loads, in kN)

CONCLUSIONS

The use of aluminium as a structural material having a good esthetic appearance may be a reason for architects to choose for aluminium. A specific canopy design, where the architect was catched by the idea of using perforated aluminium plates as a main bearing structure, has lead to difficulties in calculations to be carried out in practice.

Until so far structural perforated aluminium can only be checked and calculated when it is loaded by tension. Perforated aluminium plates loaded by compression should be checked on strength and stability, which is not taken into account in present regulations as the Eurocodes. To tackle this problem extended analytical, numerical and experimental research should be carried out. The projects described in this document (ref. [1] and [3] to [7]) can be seen as a first step in this research.

RECOMMENDATIONS

It is recommended to extend the numerical an experimental research on perforated aluminium plates loaded by compression to a fundamental analytical approach.

Aluminium is a high qualitative material with esthetic as well as structural properties. To be able to use these special qualities standard regulations for aluminium structures are not fulfilling designer's requirements.

REFERENCES

[1] Reitsema, A.D., ' Research on the tensile and compressive strength of perforated aluminium plates for different perforation patterns (in Dutch)', internal report TU/e, July 2010.

[2] NEN -EN 1999 Part 1.1, 'Eurocode 9 Design of aluminium structures – General rules and rules for buildings', 2007.

[3] Aa, A. van der, 'Realisation and cost reduction of a perforated aluminium roof structure (in Dutch)', internal TU/e report, December 2010.

[4] Chakiri, H., 'Local buckling behaviour of perforated aluminium plates (in Dutch)', internal TU/e report, June 2011.

[5] Dun, J.P. van, 'The influence of perforations on local buckling behabiour of aluminium plates loaded by compression (in Dutch)', februari 2011.

[6] Lelivelt, R.J.J., 'FEM analysis of perforated plates loaded by compression (in Dutch), internal TU/e report, Januari 6th 2013.

[7] Lenselink, S, ‘ Numerical analysis of aluminium plates loaded by compression (in Dutch)’, internal report TU/e, June 2013

[8] Bakker, M.C.M., Rosmanit, M., and Hofmeyer, H., ‘Prediction of the elasto-plastic post-buckling strength of uniformly compressed plates from the fictitious elastic strain at failure’, Thin-Walled Structures 47 (2009), 1-13.