Effects of Hail Damage on the Carrying Capacity of Standing Seam Profiles

A. Hubner

H. Saal

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Hübner, A.[1] and Saal, H.[2]

Abstract

Industrially prefabricated aluminum standing seam systems are used in the construction of facades and roofs. The standing seam profiles can be quickly assembled with special zipping machines to form roof systems. The load carrying capacity of standing seam profiles has been established by experiments according to a standardized procedure for thin–walled trapezoidal sheeting.
During a thunderstorm the roof of a book warehouse constructed from standing seam profiles suffered unexpectedly heavy damage by the impact of hailstones. This problem is discussed in the present paper. The research deals with the effect of hail dents on the carrying capacity of the profiles. The results of the experimental load carrying capacity of the damaged panels are compared to analytical results for damaged and undamaged panels. The influence of the dents is analyzed and possible solutions for better prediction of likely damages are presented.

1. Introduction

In May 2003 a major thunderstorm came down in the south of Germany. The thunderstorm was accompanied by a heavy hailstorm with hailstones in the size of tennis balls. In the event the book warehouses of a logistic company were heavily damaged. Along with other physical damage the aluminum roofs of the warehouses were damaged and domelights in the roof broken. The following concentrated efforts of the fire brigade in order to prevent water from penetrating the buildings caused further damage to the roof due to improper access.

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[1] Research Assistant, Lehrstuhl für Stahl- und Leichtmetallbau, Universität Karlsruhe (TH), D-76128 Karlsruhe, Germany
[2] Full Professor, idem.

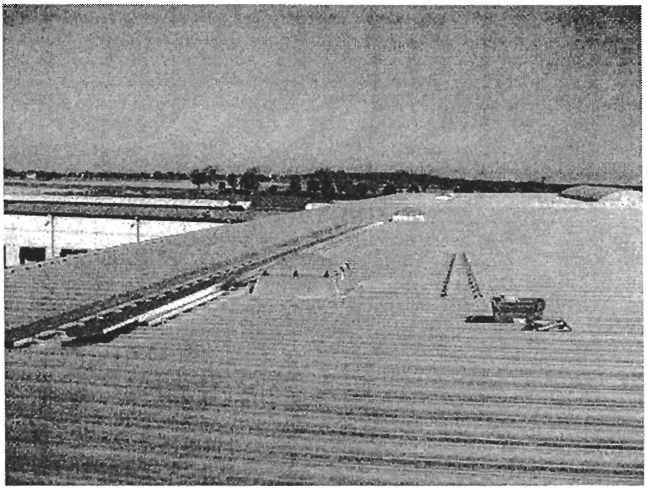

Figure 1: Roof of the warehouse

These facts raised the question whether under the given circumstances the carrying capacity of the roof was still satisfactory or a re-construction was necessary. The research presented deals with the effect of hail dents on the carrying capacity of the profiles. In the first step of the investigation experiments were conducted in order to obtain results for damaged and undamaged panels and the results of the experiments are described. In the second step numerical analyses were performed and compared with the experiments with the aim of analyzing the influence of the dents. A possible solution for taking hail-damage into account is presented.

2. Project Description

Figure 1 depicts the roof of the warehouse with domelights. The warehouse consists of two buildings with the dimensions L/W/H=37m/90m/8m and L/W/H=40.50m/162m/16m.

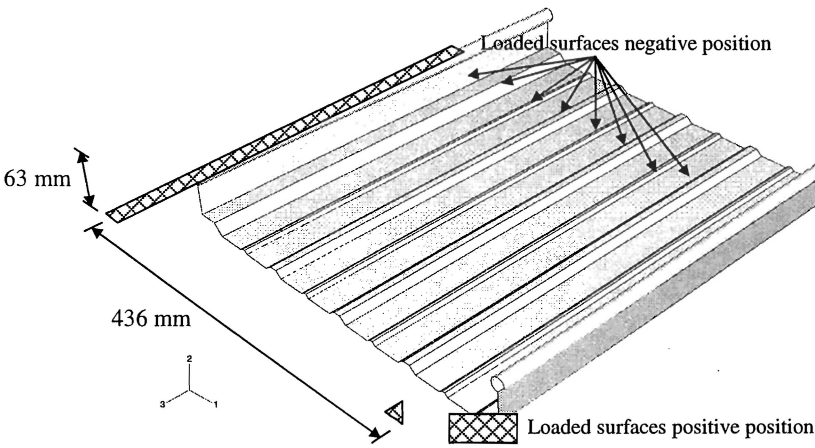

Figure 2: Standing seam profile 63/400

The roofing is constructed by using a prefabricated aluminum standing seam system. The standing seam profiles with a stucco-embossed surface have a construction width of 436 mm, a height of 63 mm (Figure 2), and a thickness of t=0.8 mm. The aluminum alloy is a EN AW-3005 (EN AW-ALMn1Mg0.5) following the DIN EN 573-3 [1] and the DIN EN 485-2 [2].

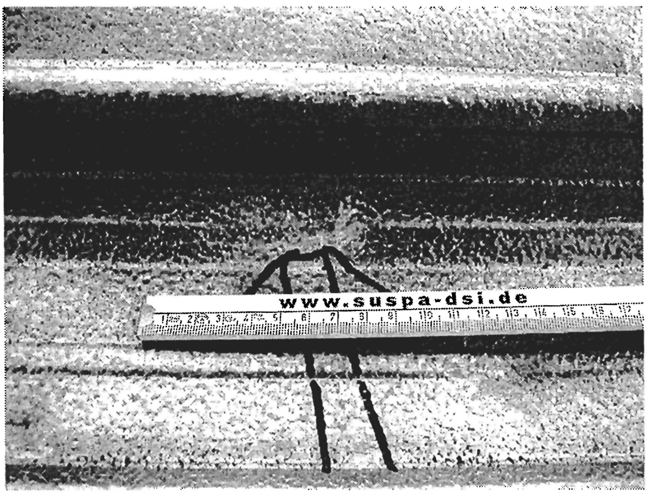

Figure 3: Example for dents

The damaged profiles had dents approximately every 10 cm with a diameter of around 4 cm as seen in Figure 3. The mapping of the dents is described more detailed in Section 4.

3. Experiments

Several experiments were conducted in the laboratories of the Versuchsanstalt für Stahl, Holz und Steine in order to obtain values for the carrying capacity of damaged and undamaged standing seam profiles. The experimental setup (Figure 4) followed the descriptions in a German code for evaluation and execution of ultimate strength tests for trapezoidal sheetings [3]. The experiments involved singled spanned profiles with the seam showing upwards (positive position) and the seam showing downwards (negative position) whilst loading from the top. The aim was to obtain values for the maximum bending moment at midspan without transverse forces for vertical loading (e.g. snow) and suction (wind load).

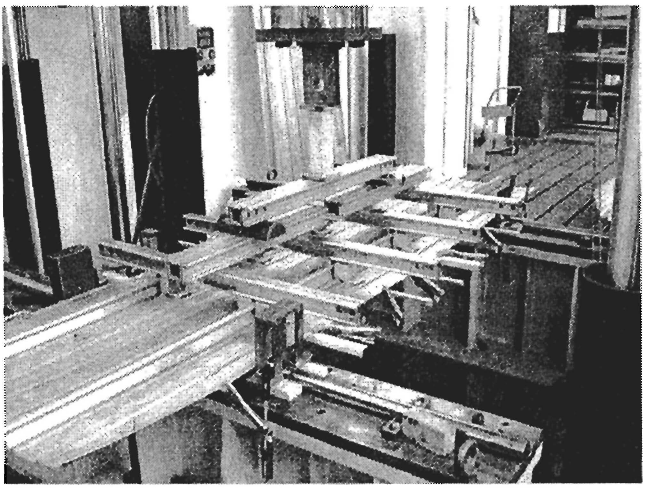

Figure 4: Experimental setup for positive position

The two supports at the ends allowed the profiles to rotate freely. The load was introduced at four points resulting in a constant moment at midspan where the deflection was continuously measured at two points.
The experiments were repeated four times for each position and the obtained maximum loads were evaluated statistically [4]. Then the values are normalized

regarding the deviations between sheet thickness and yield stress of the specimens and the nominal thickness of the profiles and the minimum required yield stress for the used aluminum alloy as follows:

$$\overline{F}_5 = F_5 \cdot \left[\frac{\min \beta_z}{\beta_z}\right] \cdot \left[\frac{\min t}{t}\right] \quad \text{with} \quad F_5 = F_m - 2 \cdot s$$

in which:

$\min \beta_z$ and $\min t$	nominal values for yield stress and thickness
β_z and t	experimental values for yield stress and thickness
F_5	characteristic ultimate load evaluated statistically
F_m	average value of the ultimate loads
s	standard deviation

if $\dfrac{\min \beta_z}{\beta_z} > 1$ then $\dfrac{\min \beta_z}{\beta_z} = 1$

$\dfrac{\min t}{t} > 1$ then $\dfrac{\min t}{t} = 1$

Table 1 summarizes the results from the experiments of damaged and undamaged panels.

Table 1: Characteristic values for the maximum bending moment in midspan for the profiles from experiments

Experiment Case	Maximum midspan moment M_{cF}	
	positive position	**negative position**
Undamaged	1.26 kNm/m	1.17 kNm/m
Damaged	1.04 kNm/m	0.97 kNm/m
Reduction	-17.3 %	- 17.1 %

The reduction in carrying capacity is described in the last line of Table 1. The dents influence the ultimate strength of the panels in positive and negative position due to the fact that its base plate is subjected to pressure and the base plate showed serious damaged caused by the hailstones especially near the seams (Figure 3). The loss is nearly the same for both load cases and can be evaluated with around 17 % loss of carrying capacity.

4. Numerical Analyses

The numerical analyses were performed with the well-known and sophisticated Finite Element program ABAQUS. In the first step of the numerical investigation undamaged standing seam profiles were modeled. The experimental setup with one whole panel and two half panels as shown in Section 3 was implemented in ABAQUS with the exception that only half of the model was simulated by applying symmetry conditions. The non-linear material properties implemented into the numerical model were based on tensile tests performed with the aluminum alloy of the profiles (Figure 5).

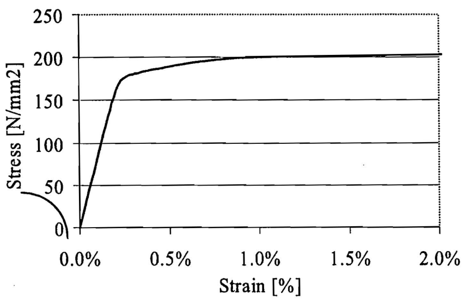

Figure 5: Implemented material properties

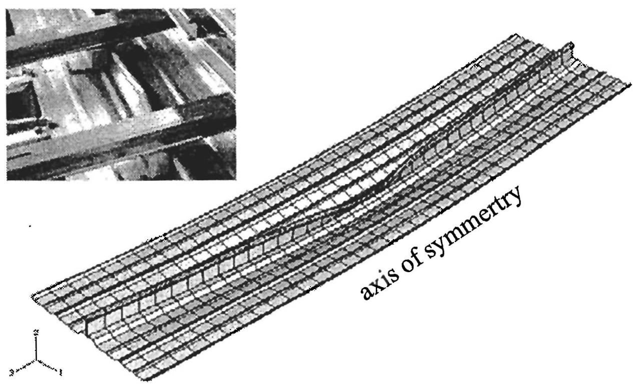

Figure 6: Deformed Profile at maximum load (positive position)

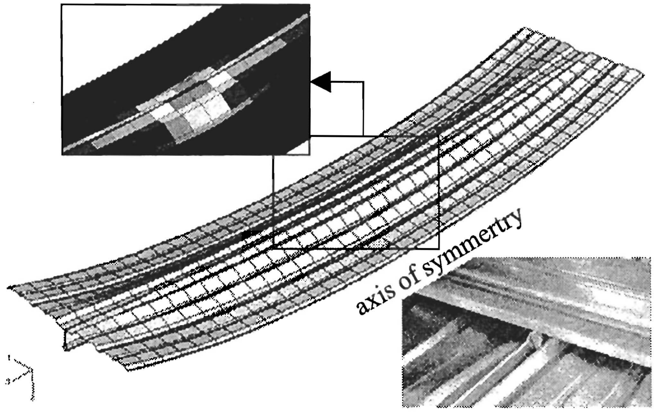

Figure 7: Deformed profile at maximum load (negative position)

In the load case positive position the model was loaded with a constant pressure close to the seam in the marked area as depicted in Figure 2. In the load case negative position the panels were loaded by applying pressure to certain surfaces as seen in Figure 2 similar to the experimental loading. This modeling with a continuous loading approximates the experimental loading which was conducted with four loads (Figure 4) sufficiently as proven in preliminary investigations not presented here.

The analyses were performed in two steps. First, a linear buckling analysis (eigenvalue prediction) was performed and the failure eigenmode extracted. In the following step a geometrical and material non-linear load-displacement analysis (involving the Riks method) with an eigenmode-affine imperfection with a maximum deformation of 0.25t based on the previous step was performed.

Figure 6 shows the deformed profile in positive position at maximum load. The failure is induced by the stability loss of the seam that acts as a compression member as it can be clearly seen in the FE plot as well as in the picture taken during the experiment. The failure mode of the loaded profile in negative position is different. Figure 7 shows the deformed profile close to its carrying capacity. The failure occurs because the yield stress near the seam is reached due to compression in the base plate, leading to a collapse of the structure. The detailed FE plot in Figure 7 depicts the appearing plastic strains (bright gray corresponds to high plastic strains). The area of large plastic deformations is depicted in the photograph in Figure 7.

The ultimate strength loads of the finite element calculations are normalized and evaluated statistically as shown in the previous section and summarized in Table 2.

Table 2: Comparison of the characteristic values for undamaged profiles from experiment and numerical analyses

Undamaged Analyses	**Maximum midspan moment M_{cF}**	
	positive position	**negative position**
Numerical	1.31 kNm/m	1.30 kNm/m
Experimental	1.26 kNm/m	1.17 kNm/m

The maximum load values for the FE calculation exceed the experimental values by 4 to 11 %. The differences in the load carrying capacity appear among other things because the experimental values are normalized based on averaged thicknesses and yield stresses which may differ between the tests. Furthermore, the loading and the boundary conditions are only approximated in the FE model and therefore the moment distribution is different. Still, close agreement between experiment and numerical calculations can be found.

5. Numerical Analyses of the Damaged Panels

For the analyses of the damaged panels an approach based on suggestions for the calculation of regularly punched plates is used. Schardt [5] proposes equivalent thicknesses for punched plates with transverse and in-plane loading. His theory is based on a regular grid of holes with the same diameter d and distance a between the centers of the holes. The analytical approaches were affirmed with numerical analyses. The standing seam profiles act as plates and therefore the following formula is proposed:

$$\bar{t}_m = \sqrt[3]{\frac{\bar{K} \cdot \left(1 - \bar{\beta}^2\right)}{K \cdot \left(1 - \beta^2\right)}} \cdot t$$ which can be approximated with

$$\bar{t}_m = \sqrt[3]{\frac{\bar{K}}{K}} \cdot t$$

in which:

$\bar{t}_m$	equivalent thickness
K and $\overline{K}$	plate stiffness and equivalent plate stiffness
β and $\bar{\beta}$	value for taking the transverse warping into account

The calculations of the damaged profiles are based on Schardt's theory [5] assuming that the damaged parts cannot contribute any stiffness to the carrying capacity of the profiles and hence can be approximated as holes. The tested panels were inspected thoroughly and the dents measured and mapped. A major difference is that the theory is based on a regular grid of holes whilst the damaged panels show areas with a large number of dents and areas with small amounts of damages. Hence, it was chosen to model two cases. In the first case the size of all dents and their distances were measured and average values obtained. This procedure led to a ratio of $d/a = 0.2$. In the second case the ratio was based on a critical area meaning that a severely damaged area with five to six dents was chosen and evaluated. Reducing the mapped area to the most heavily damaged region leads to a ratio of $d/a = 0.5$. With this method a lower and an upper boundary for the carrying capacity were created. Applying the proposed formulas and table the equivalent thickness can be approximated:

$$d/a = 0.2 \rightarrow 0.5 \quad \Rightarrow \quad \overline{K}/K = 0.920 \rightarrow 0.604$$

$$\bar{t}_m = 0.97t \rightarrow 0.85t$$

With the equivalent thickness of 0.67 mm and 0.78 mm the same analyses as for undamaged profiles were performed. Table 3 sums up the normalized and statistically evaluated results from the numerical analyses. The influence of the dents or the holes reduces the load carrying capacity by at least 3.8 % to a maximum of 20.8 % of.

Table 3: Characteristic values for the maximum bending moment in midspan for the profiles from numerical analyses

Numerical Case	**Maximum midspan moment M_{cF}**	
	positive position	**negative position**
Undamaged	1.31 kNm/m	1.30 kNm/m
Damaged	< 1.26 kNm/m > 1.06 kNm/m	< 1.25 kNm/m > 1.03 kNm/m
Reduction	-3.8 % to -19.4 %	-3.9 % to -20.8 %

The findings from the experiments showed a loss of around 17 % of the carrying capacity. The experimental value fits between the lower and the upper boundary given by the numerical analyses (Table 3). The test results tend towards the lower boundary for the bearable midspan moment which is defined under the assumption that the worst damaged area controls the carrying behavior.

6. Conclusions

The ultimate strength of aluminium standing seam profiles was predicted by experimental and numerical means. The numerical analyses were based on data gained by performing material tensile tests of the aluminium alloy. In the following stage heavily damaged standing seam profiles were investigated by applying a method for punched plates with an equivalent thickness. The case of profiles severely damaged by the impact of hailstones served as a reference.
While several assumptions had to be made in the investigation, including equating regular holes with irregular dents, the following conclusions can be drawn from the study.

1. The influence of hail damage in terms of dents decreases the carrying capacity of standing seams profiles noticeably and hence must not be neglected.
2. In a first approximation the dents can be assumed to act as holes, calculating the reduced carrying capacity with an equivalent thickness.
3. It appears that rather a local accumulation of dents controls the ultimate strength of standing seam profiles then the average distribution of dents over the profiles.

7. References

[1] DIN EN 573-3, November 1994.
[2] DIN EN 485-2, August 1994.
[3] DIN 18807-1 to 3, June 1987.
[4] Arbeitskreis „Stahltrapezprofile" der Prüfämter für Baustatik „Musterbeispiel für die Auswertung von Traglastversuchen nach DIN 18807 Teil 2 zum Nachweis der Sicherheit von Stahltrapezprofilen", Berlin, December 1990.
[5] Schardt, R., Bollinger, K., Zur Berechnung regelmäßig gelochter Scheiben und Platten, Bauingenieur 56, p227-239, 1981.