# PROFILED SHEET METAL STRENGTH UNDER VARIOUS PATCH LOADS USING NONLINEAR FEA

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***Summary:*** *Profiled sheets are widely used in modern steel structures, either as cladding or as casing in composite structures. Their strength calculation is a complex task because of their complicated cross-section shape. Manufacturer's catalogues provide data about their strength, often for continious surface load, but rarely for patch loads. In this research, the Finite Element Method (FEM) analysis with geometrical and material nonlinearity and contact analysis in the support zones was applied for the strength calculation of one typical profiled steel sheet. The analysis encompassed several patch load patterns. Results of the research showed that such elements can withstand relatively high localized loads, and that ultimate load depends much on the patch load position in transversal direction.*

***Keywords:*** *profiled steel sheet; strength; nonlinear FEM analysis; patch load;*

## 1. INTRODUCTION

Profiled trapezoidal metal sheets have broad application in building structures, especially when combined with steel bearing structures. They are used for making roof and façade cladding, and often as a permanent casing of reinforced concrete and composite ceilings [1]. Common manufacturing width of the sheets is 800 do 1100 mm, while the length is limited by road transport vehicles to 12000 mm. Sheet thickness is usually 0.5-1.5 mm. Profile shape may be various, whereat the web height and sheet thickness predominantly affect the element strength, together with the supporting conditions, and number of fasteners. For standard profile types, manufacturers regularly provide the strength of those elements, which is commonly expressed as ultimate load and load at limited deflection. The strength is usually given for surface load. Patch loads are rarely treated in catalogues, although they are often present in various positions and combinations.

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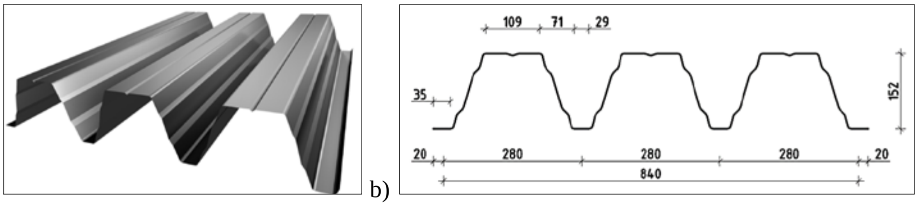
The most often method of strength determination for such structures is analytical, which assumes the profiled sheet as a line girder. Experimental methods [2] are also used, but they demand reliable experimental equipment, qualified operators, and significant cost. Finally, strength determination can be also efficiently performed by FEM and advanced software that enable nonlinear analysis in geometrical and material domain.

## 2. SETTING OF THE PROBLEM

In this paper, the strength of a standard trapezoidal steel sheet denoted as 150/280, was analysed (Fig. 1). This type of trapezoidal steel sheet is produced by many manufacturers worldwide. The analysis of strength was done using FEM, and the obtained results were compared with other sources and methods. Subject of the analysis was one sheet, 840 mm wide, set horizontally over span of 9000 mm. The sheet was supported on two steel plates acting as purlin flanges, which were not subject of the analysis. The adopted steel material was S235, and the sheet thickness was 1.00 mm.




a) b)

*Fig. 1. Trapezoidal sheet 150/280; a) view; b) geometry.*

## 3. FEM MODELLING

### 3.1 Geometry and material

The FE model consisted of three separate bodies: sheet metal (1 mm thick) and two supporting plates (10 mm thick). The working diagram for steel, $\sigma$-$\varepsilon$, is represented by bilinear function with kinematic hardening. The modulus of elasticity was E=210 GPa, yield point $f_y$=235 MPa, and the tangent modulus of elasticity was $E_T$=0.01E=2.1 GPa (Fig. 2). Fastening of the profiled sheets with the purlins is commonly realized using self-tapping screws. Here they were modelled as line elements of BEAM type, with cross section characteristics according to the fastening device diameter (Ø5 mm). Material behaviour of the fastener was adopted as elastic.

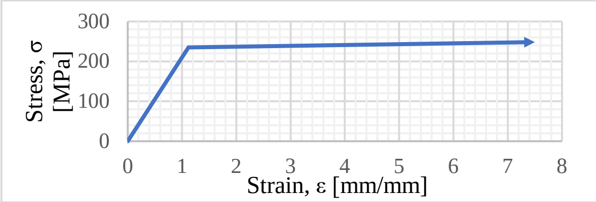



*Fig. 2. Working diagram for steel*

### 3.2 Meshing of the model

Geometrical models were meshed by shell finite elements, and special contact connection elements were used at the locations where the profiled sheet rests on the purlins. The mesh density was locally increased near supports, across the length of 400 mm. Global element size was 40 mm, and local, in the support area, 20 mm (Fig. 3) [3].

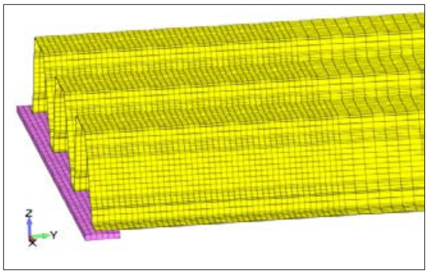


*Fig. 3. Mesh density, detail of the support;*

### 3.3 Boundary conditions, load and analysis parameters

Resting of the profiled sheet on the support plates implies compression forces transferring from the sheet to the plates, but also separation of some parts of the sheet due to its deformation. Because of that, contact analysis was applied, which enables that compression forces can be generated, but not tension. The longitudinal displacements (Y-direction) of the profiled sheet metal were set as restrained on one end, and free on the other end, that is, one purlin was movable in Y-direction. The analysis was done for 2 support conditions: a) Z=2 fasteners and support width B=40 mm; b) Z=8 fasteners and support width B=200 mm. Load was applied on patch surfaces approx. 100x100 mm, with intensity of 5 kN per one patch. All load patches were set at midspan, with 5 different load patterns (Fig. 4). The load was acting over the top flanges of the sheet metal.

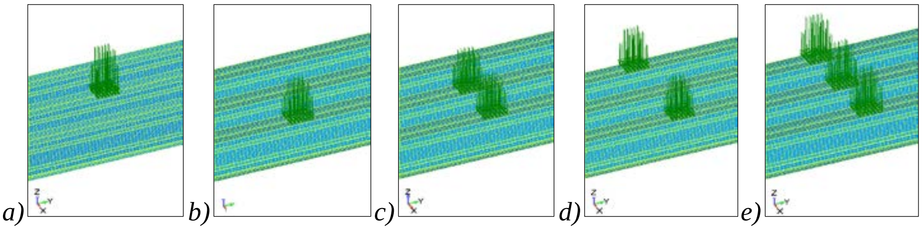



*Fig. 4. Load patterns: a) P1; b) P2; c) P1+P2; d) P1+P3; e) P1+P2+P3;*

A nonlinear static analysis with geometrical and material nonlinearity was conducted, using software FEMAP with NX NASTRAN [4]. The geometrical nonlinearity included large displacements, to predict possible buckling. The material nonlinearity allows for the plasticization of the structure. The load was applied incrementally, in 20 steps.

## 4. FEM ANALYSIS RESULTS

### 4.1 Ultimate load

The FEM analysis results regarding ultimate load, max. stress, and deflection are presented in Table 1. Comparative values of the ultimate load for two applied support conditions are given in Fig. 5.

*Table 1. FEA results (L=9000 mm)*

| Group | Model label | Load pattern | ΣP [kN] | B [mm] | Z [-] | $p_{ult}$ [kN] | $\sigma_{equ}$ [MPa] | $y_{max}$ [mm] | L/y [-] |
|---|---|---|---|---|---|---|---|---|---|
| A1 | L9-Z2-B040 (P2) | ○○● | 5 | 40 | 2 | 2.25 | 292 | 111 | 81 |
| A2 | L9-Z2-B040 (P1) | ○●○ | 5 | 40 | 2 | 3.21 | 295 | 123 | 73 |
| A3 | L9-Z2-B040 (P1+P2) | ○●● | 10 | 40 | 2 | 3.68 | 303 | 112 | 80 |
| A4 | L9-Z2-B040 (P2+P3) | ●○● | 10 | 40 | 2 | 2.75 | 266 | 51 | 176 |
| A5 | L9-Z2-B040 (P1+P2+P3) | ●●● | 15 | 40 | 2 | 5.34 | 304 | 110 | 82 |
| B1 | L9-Z8-B200 (P2) | ○○● | 5 | 200 | 8 | 2.34 | 289 | 95 | 95 |
| B2 | L9-Z8-B200 (P1) | ○●○ | 5 | 200 | 8 | 3.41 | 313 | 125 | 72 |
| B3 | L9-Z8-B200 (P1+P2) | ○●● | 10 | 200 | 8 | 3.99 | 305 | 111 | 81 |
| B4 | L9-Z8-B200 (P2+P3) | ●○● | 10 | 200 | 8 | 5.18 | 305 | 113 | 80 |
| B5 | L9-Z8-B200 (P1+P2+P3) | ●●● | 15 | 200 | 8 | 5.70 | 309 | 109 | 83 |

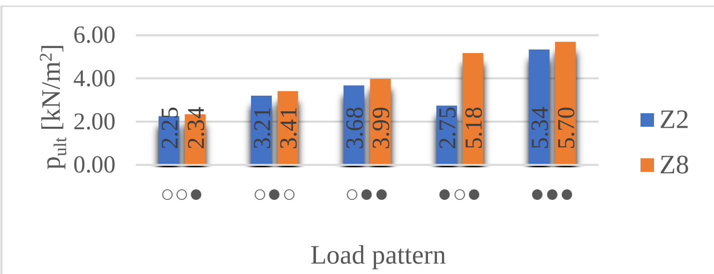



*Fig. 5. Ultimate load values for different load patterns and various support conditions*

From the Fig. 5 one may note that the model group "B" always gives higher values of ultimate load for same load pattern. The difference ranges from 4-8%. Reason for this is obviously the way of supporting. Namely, the model group with support width B=40 mm and number of fasteners Z=2 is closer to the pin joint, while the model group with support width B=200 mm and number of fasteners Z=8 is closer to the fixed joint. Manufacturer's catalogues sometimes provide the data about the support width, and they vary from 40 to 230 mm [5, 6, 7, 8, 9, 10], but not the number of fasteners. This analysis example shows that number of fasteners may be of prominent importance, so the catalogues should include corresponding guidelines.

Next important observation is that generally all models withstand patch loads that are far higher than common design value of P=1 kN, which substitutes load from one workman at the most unfavourable place in the structure. Bearing capacity of the structure exceeds the nominal value of 1 kN from 225 up to 570 %. This phenomenon points to the existence of significant load reserve, which can be of crucial importance in case of accidental loading.

Besides the pure load intensity, the load disposition also plays prominent role. It is well-known that design codes demand setting of the patch (or concentrated) load at "the most unfavourable location", as mentioned above. It implies the midspan regarding the longitudinal direction, but nothing is said about the transverse postion of the load. From this research, one may see that symmetrically set loads produce higher ultimate strength than the unsymmetrical. Moreover, increasing of the patch number from one to two, and finally three patches, gives higher strength values.

### 4.2 Local deformation

Following the results given in Fig. 5, further considerations regarding strength are limited to the model group "*B*", as a more efficient one. Fig. 6 presents total deformation contours for group model "*B*" (from the lowest to the highest), and based on it, corresponding observations regarding local deformation are derived:

1. B1 – one asymmetric force; shows high local deformation, as vertical, as well as lateral; the opposite profile wave (left) takes no part in load reception, the middle one takes some part of the load.
2. B2 – one symmetric force in the middle crest; modest local deformation; both outer profile waves take part in load reception.
3. B3 – two forces set assymmetrically; local deformation is prominent, especially at the outer wave; again, the unloaded wave takes little part in load reception.
4. B4 – two forces set symmetrically; local deformation is present but lower than in B3; the middle (unloaded) wave takes part in load reception, especially the ribs.
5. B5 – three forces set symmetrically; local deformation is present but lower than in B3 and B4, the highest is in the middle; outer waves take part in load reception and prevent large lateral deformation.

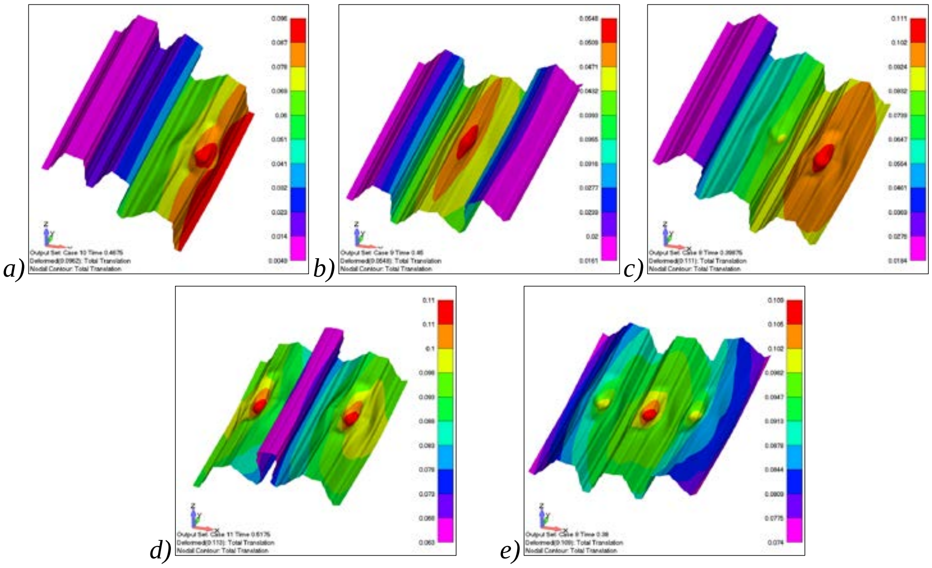


*Fig. 6. Total deformation contours for group model B; a) B1; b) B2; c) B3; d) B4; e) B5.*

The observations given above imply two interesting facts:

a) first, lateral symmetry in loading improves the structural behaviour, i.e., its strength;

b) second, higher number of load spots improves the structural behaviour, i.e., its strength.

Here it must be remarked that all patch loads had the same intensity of 5 kN, meaning that total load intensity varied depending on the patch load number fom 5-15 kN. Irrespective of this, the obtained ultimate load always stands for total load. Consequence of this is that ultimate load should be distributed in optimal way in order to achieve max. strength. The most optimal way, according to this research is three forces set symmetrically. Of course, if the construction condition require loading in two, or one point (patch), than the symmetry principle should be applied.

### 4.3 Local stresses

The local stress values near the load patches (Fig. 7) do not follow the strength rank described above. Namely, the best model regarding ultimate load, *B3*, with two forces set assymmetrically, exhibited the highest local stresses (299 MPa). Interesting, the model *B2*, with one symmetric force in the middle crest showed the lowest stress values (243 MPa). Nevertheless, overall stress differences do not exceed 19 %. Excluding the model B2, the differences drop to only 6 %, which confirms the reliability of the numerical model. On the other hand, all stress values exceed the yield point for the adopted steel material (235 MPa). However, one must bear in mind that the analysis shows ultimate values, without any safety factor implemented, which would be mandatory for design practice.

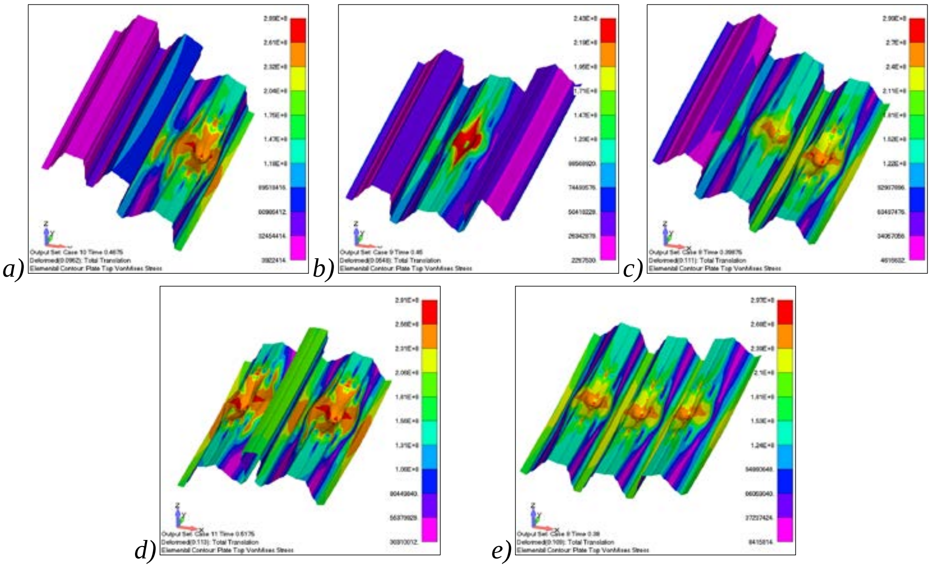



*Fig. 7. Von Mises stress contours for group model B; a) B1; b) B2; c) B3; d) B4; e) B5.*

It has to be added that in most models the local max. stress values in the vicinity of the loaded patches were at the same time the max. values for the whole model. Nevertheless, there were three exceptions, which are presented in Fig. 8. Namely, in those models the max. stresses were located at the supports, implying that supporting zones can be as critical as the load zones. However, stress levels at those supports were very close to those in the loaded regions.

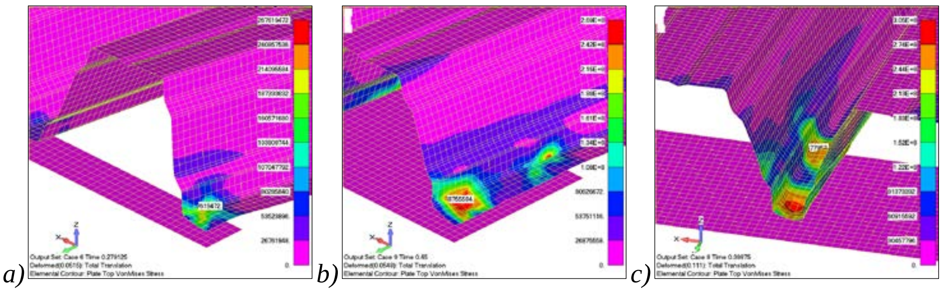



*Fig. 8. Von Mises stress contours – absolute maximum;*
*a) L9-Z2-B040 (P2+P3); b) L9-Z8-B200 (P1); c) L9-Z8-B200 (P1+P2)*

### 4.4 Practical considerations

The research started from the idea that structural strength of the profiled steel sheets under patch loads is insufficiently investigated, and that data about it is scarce. The most common application of patch load is, as mentioned, the occasional (or accidental) load from a workman on the roof. For such case, the obtained results do not provide satisfying recommendations since they dictate specified load disposition for optimal strength results, while the moving of the people on the roof is unpredictable. However, there are many practical cases where patch loads are implemented, e.g., mounting of antennas, flagpoles, ventilation ducts, lightning rods, and various equipment. For such cases, the consideration of optimal way of patch loading may be of high interest. The usual practice regarding the mounting of different installations over profiled sheet roof includes certain stiffenings, like plates, or doubling the profiled sheet. Thereat, the design engineer often does not dispose of reliable data considering the strength of the stucture. This research provides a reliable numerical model and gives useful guidelines for such cases, without need for any additional structural elements.

## 5. CONCLUSIONS

The research treated strength of one typical trapezoidal steel sheet intended for long spans under patch loads. Manufacturers typically provide strength data regarding surface loads, but strength under patch loads is insufficiently investigated, and data about it is scarce. Here, two ways of structural supports, close to real practice, were considered: one close to the pinned support, and the other close to the fix support. The results show that the fixed supports give somewhat higher strength.
All analysed cases showed that the structure can withstand patch load that is far higher than the common code requirement of 1 kN, that is, the load reserve is 225 to 570 %.
The ultimate strength higly depended on the patch load position has. First, the lateral symmetry in loading improves the structural behaviour, i.e., its strength; second, higher number of load spots has the same effect.
Max. stresses are in most cases in the load zones, but, in some cases, the supporting zones can be also critical, so attention must be paid to those regions.
The conducted research may have significant practical use, especially for mounting of additional structures and devices on the sheet roof, like antennas, flagpoles, ventilation ducts, lightning rods, and various equipment. The research results provide optimal ways of mounting of such structures, and a reliable numerical model for design.

## Acknowledgements and funding

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# НОСИВОСТ ПРОФИЛИСАНИХ ЛИМОВА НА ЛОКАЛНА ОПТЕРЕЋЕЊА ПРИМЕНОМ МКЕ

***Резиме:*** *Профилисани лимови су у широкој употреби у савременим челичним конструкцијама, било као облога, или као оплата код спрегнутих конструкција. Прорачун њихове носивости је комплексан због њиховог сложеног попречног пресека. Каталози произвођача дају податке о носивости, обично за површинско оптерећење, а ретко за локализовано оптерећење. У овом истраживању је примењена анализа Методом коначних елемената (МКЕ) са геометријском и материјалном нелинеарношћу, као контактна анализа у зони ослонаца за прорачун носивости једног типичног профилисаног лима. Анализа је обухватила неколико шема локализованог оптерећења. Резултати истраживања су показали да овакви елементи могу поднети релативно велика локализована оптерећења, а да гранична носивост зависи умногоме од положаја оптерећења у попречном правцу.*

***Кључне речи:*** *профилисани лим; носивост; МКЕ; локализовано оптерећење;*