Determination of Profiled Sheet Metal Strength under Standard Testing Loads Using Nonlinear FEA

Todor Vacev 1, Milos Milic 1, Ivan Nesovic 1, Andrija Zoric 1

1 Faculty of Civil Engineering and Architecture, University of Niš, A. Medvedeva 14, Niš, Serbia
todor.vacev@gaf.ni.ac.rs

Abstract. Profiled sheets are widely used in modern steel structures, either as cladding or as casing in composite structures. Their strength calculation represents a complex task because one must deal with thin-walled structures that have complicated cross-section shape. Manufacturer’s catalogues provide data about their strength, mostly for continuous surface load. These data are mostly obtained by testing. EUROCODE EN 1993-1-3, i.e., its Annex A2, regulates the testing procedures for profiled sheets, allowing two main approaches regarding load application: uniformly distributed load and equivalent line load (in four locations). In addition, the mentioned code proposes roller supports that simulate pinned joints at the ends, neglecting the fastening conditions, which unavoidably are present with these structures. Aim of this research was to prove if the two proposed load patterns produce identical results, and to reveal how fastening devices affect the structural strength. In this research, the Finite Element Method (FEM) analysis with geometrical and material nonlinearity and contact analysis in the support zones were applied for the strength calculation of one typical profiled steel sheet. The analysis was conducted for ultimate load strength and for maximum load at standard deflection of L/200. In order to provide the testing conditions as real as possible, the support conditions were set in two ways: a) with support width B=40 mm and N=2 fasteners at the support, i.e., one fastener in each outer trough; b) with support width B=200 mm and N=8 fasteners at the support, i.e., two fasteners per every trough. The first support case is intended to simulate behavior close to a simply supported beam, and the second should simulate a beam fixed at its ends. The analysis encompassed the two load patterns provided by EUROCODE standard, and the results were compared. The results reveal that the surface load approach gives higher strength values than the four-point-load, both for ultimate load and for maximum load at deflection of L/200. This stands for both analyzed support conditions. The results of the research indicate that the codes should much more precisely define the testing conditions for such structures and make them closer to reality, for the purpose of more reliable and economic design.

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 to 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, whereas 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.

The most reliable method of strength determination for such structures is experimental, and it is regularly used by manufacturers in order to supply strength data in their catalogues. Testing procedures may vary and produce diverse results, so it is of utmost significance to use standard approach. The European standard EN 1993-1-3, Annex A2, provides mandatory conditions for such testing, but allows for two alternative approaches regarding load application: surface load and the so-called four-point-load.

Aim of this research was to prove if the two proposed load patterns produce identical results, that is, to check if their mutual alteration is justified.

For that purpose, 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 was conducted for ultimate load strength and for maximum load at standard deflection of L/200. The software used was FEMAP-NASTRAN [2].

2. Setting of the problem

For this research, a standard trapezoidal steel sheet denoted as 150/280 was chosen (Figure 1). This type of trapezoidal steel sheet is produced by many manufacturers worldwide. Two load patterns proposed by EUROCODE [3] were analyzed, and the obtained results were mutually compared. Subject of the analysis was one sheet, 840 mm wide, set horizontally over a 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.

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), which simulate roof purlins. The working diagram for steel, $\sigma$-$\epsilon$, 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 (Figure 2a). 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 ($\Omega 5$ mm). Material behavior of the fastener was adopted as elastic.

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

Figure 2. a) Working diagram for steel; b) Mesh density, detail of the support.
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 the supports, across the length of 400 mm. Global element size was 40 mm, and local, in the support area, 20 mm (Figure 2b).

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) N=2 fasteners and support width B=40 mm; b) N=8 fasteners and support width B=200 mm. Load was applied in two ways, according to the standard [3]: a) as surface load acting over the top flanges of the sheet metal (Figure 3a); b) in four points (Figure 3b). Load application used in FEM analysis is presented in Figure 4 and Figure 5. In fact, the four-point load was also surface load, applied on top flanges on area of approx. 0.01 m² (Figure 5b).

A nonlinear static analysis with geometrical and material nonlinearity was conducted. 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 results reveal that the surface load approach gives higher strength values than the four-point-load (Table 1, Fig. 6). For support condition close to the simply supported beam, that is, B=40 mm, and N=2, the surface load case gave ultimate load value that was 5.1% higher. The near-fixed beam, with B=200 mm, and N=8, showed even higher differences. Here the strength for surface load case exceeded the four-point-load case for even 29%. Such differences put strongly into question the EUROCODE guidelines of arbitrary selection of loading.

| No. | Model         | Load pattern | B [mm] | N  | $p_{ult}$ [kN] | $p_{ult}$ [%] | $\sigma_{equ}$ [MPa] | $z_{max}$ [mm] | L/z [-] |
|-----|---------------|--------------|--------|----|----------------|---------------|----------------------|----------|--------|
| 1   | L9-N2-B040-4PL | 4 points     | 40     | 2  | 11.35          | 100.0         | 265                  | 137      | 66     |
| 2   | L9-N2-B040-SL  | surface      | 40     | 2  | 12.01          | 105.8         | 267                  | 140      | 64     |
| 3   | L9-N8-B200-4PL | 4 points     | 200    | 8  | 12.30          | 108.4         | 439                  | 134      | 67     |
| 4   | L9-N8-B200-SL  | surface      | 200    | 8  | 15.59          | 137.4         | 502                  | 155      | 58     |

Figure 6. Comparative results of the analyzed cases for ultimate load

Comparing the results between the two support conditions, one may note that the case with N=8 fasteners and support length B=200 mm produces notably higher ultimate load, 8.4% for the 4-point-load pattern, and 29.8% for surface load pattern. Again, the observed differences point to the lack of precise data in the EUROCODE EN 1993-1-3, Annex A2, this time regarding support conditions.

The deformed shapes confirm the assumptions about support conditions (Figure 7 and Figure 8). The structures shown in Figure 7a and Figure 8a exhibit rotations at the support without significant buckling, and it is close to a pin-end behavior. On the other hand, the structures presented in Figure 7b and Figure 8b clearly show certain degree of fixity, accompanied with buckling of the bottom flange.

The stresses exceed the yield point in all analyzed cases, and in the fixed-end support condition reach even 500 MPa. However, the regions of stress concentrations occur in two main regions: first, at the supports (Figure 7 and Figure 8), and second, around the load spots in the case of the 4-point-load pattern (Figure 9). The first group of locations can be procured under common stress concentrations in the vicinity of connections, usually neglected in the design process. The second one concerns to the nature of the load application, that is, the 4-point-load pattern unavoidably leads to the mentioned concentrations. Though it would be reasonable to neglect them too in the process of the evaluation of the structure, their occurrence could mislead the researcher, if the stresses should be of high interest. In other words, the 4-point-load pattern shows undesirable side effects that cannot be eliminated.
Figure 7. Ultimate load for surface load pattern; deformed shape and Mises stress contours; support detail; a) L9-N2-B040-SL; b) L9-N8-B200-SL

Figure 8. Ultimate load for 4-point-load pattern; deformed shape and Mises stress contours; support detail; a) L9-N2-B040-4PL; b) L9-N8-B200-4PL
4.2. Maximum load at deflection L/200

While the ultimate load has a more theoretical meaning, for this type of structure is of utmost interest the maximum load which the structure may withstand with certain deflection limit. In this case, common value for such limit is L/200, where L stands for span. The FEM analysis results for such conditions are given in Table 2 and Fig. 10.

Table 2. FEA results, maximum load for deflection L/200.

| No. | Model          | Load pattern | B [mm] | N [-] | $p_{L/200}$ [kN] | $p_{L/200}$ [%] | $\sigma_{eq}$ [MPa] | $y_{max}$ [mm] | L/y [-] |
|-----|----------------|--------------|--------|-------|-----------------|-----------------|-------------------|-----------------|--------|
| 1   | L9-N2-B040-4PL | 4 points     | 40     | 2     | 4.73            | 100.0           | 268               | 51              | 176    |
| 2   | L9-N2-B040-SL  | surface      | 40     | 2     | 5.00            | 105.7           | 253               | 52              | 173    |
| 3   | L9-N8-B200-4PL | 4 points     | 200    | 8     | 4.73            | 100.0           | 271               | 44              | 205    |
| 4   | L9-N8-B200-SL  | surface      | 200    | 8     | 5.13            | 108.5           | 266               | 44              | 205    |

Here it must be remarked that the load and deflection values are not absolutely precise, because of the relatively small number of load steps in the analysis. Nevertheless, the obtained results confirm the basic behavior observed in the case of ultimate load. Namely, here too the surface load pattern produces higher strength values, although the differences are lower: 5.7 % for the “pinned-end support”, and 8.5 % for the “fixed-end support”.

Figure 9. Ultimate load for 4-point-load pattern; von Mises stress contours; global view; a) L9-N2-B040-4PL; b) L9-N8-B200-4PL;

Figure 10. Comparative results of the analyzed cases for maximum load at L/200 deflection.
5. Results and discussions

The conducted analyses for two load patterns and two types of support conditions confirm the initial assumption that current procedures for testing of profiled sheets given in the appropriate EUROCODE [3] are not sufficiently precise and not unanimously determined. Namely, the FEM analysis results reveal that alternative use of the two proposed load patterns, the surface load and the four-point-load produce notably different results regarding the structural strength.

Furthermore, the support conditions given in the mentioned EUROCODE do not reflect the conditions commonly practiced in real structures. The manufacturer’s catalogues also do not pay attention to the supports [4, 5, 6, 7, 8], with rare exceptions [9]. The FEM models analyzed encompassed two realistic support cases, the first one with minimal number of fastening devices, N=2, and minimal
support length, B=40 mm, and second, with increased number of fastening devices, N=8, and increased support length, B=200 mm. The first one could be reasonably categorized as a pinned support, and the second is quite close to a fixed end support. Both are possible and applicable in roof and similar structures. As one may see, the strength values obtained by FEM analysis are not identical if various load and support conditions are applied, especially regarding the ultimate strength values.

6. Conclusions
The conducted research showed that testing procedure for determination of strength of profiled steel sheets proposed by the EUROCODE EN 1993-1-3, Annex A2 is incomplete, and can be misleading for investigators. Since the common loads related to the structures that involve profiled sheets, i.e., roof structures, are snow and wind, it follows that surface load patterns are much acceptable than the so called “four-point-load” pattern. Following the research results given in this paper, it would mean that higher strength values could be used by design engineers.

Concerning the support conditions, one may note that the mentioned code makes an oversimplification introducing a roller bearing not applicable in practice. The contact analysis applied in this research shows two possible support solutions (among many others), and proves that support conditions play an unavoidable role in total strength of the structure.

The procedures given by EUROCODE may produce meaningful results, but only in a closed set of experimental data, comparable only mutually. On the other hand, the design engineer needs concrete data that originate from concrete surrounding. This leads us to the final point of this research: determination of strength of profiled sheets is a complex task, which requires a broad investigation that includes all parameters which take part in the structure exploitation. The FEM analysis proves itself as a powerful tool for such task.

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