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Experimental Research and Integrated FEM Modelling for Sheet Roof Covering with Thermal Insulation

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FEM numerical analysis of the behaviour under loading was conducted for a coupled set of elements, i.e. cold–formed Z purlins, thermal insulation and trapezoid sheets forming a roof covering. The results gained for an integrated model built with FEM program MSC.Marc were compared with the values obtained for the true model in loading tests. A sufficient adequacy of numerical simulation was achieved.

Keywords: Cold–formed, purlin, sheet, roof, modelling, shell

1. Introduction

Steel beams from thin–walled profiles of various cross–sections e.g. Z, C, sigma are widely applied as supporting elements in modern trapezoid sheet roof coverings at present [1, 2]. In these types of structures a beam–sheet [3, 4] and a beam–insulation–sheet co–action plays a fundamental role.

In order to clarify the above mentioned phenomenon a numerical analysis for a coupled set of elements forming a roof covering under loading was carried out. A numerical model using shell finite elements (for steel profiles and roof sheets) as well as brick elements (for insulation blankets) was elaborated for the roof covering as a whole, so that the interaction between the beams and the trapezoid sheets was reflected more precisely than in other approaches to the problem. The experimental research was conducted at the Cracow University of Technology (CUT).

2. Experimental research

2.1. *Description of test model*

The test model was a section of the load–bearing construction of a roof covering being in use for instance in lightweight single–storey buildings (Fig. 1). Three purlins with the length of 6.0 m from cold–formed Z250 2 mm thick made of S350GD steel were applied. BTD 45/1000 trapezoid sheet with the gauge of 0.5 mm made of S280GD steel was fixed to each purlin placed at the 1.5 m distance using OC – 63038 Koelner self–driving screws with washers of EPDM in the span of 333 mm. Trapezoid steel sheets were connected to each other with overlaps using OCW – 48016 Koelner self–driving screws with washers of EPDM in the span of 450 mm. The roof insulation consisted of fibre glass blankets Uni–Mata Alu 100 mm thick. It was covered with an aluminium moisture and a vapour barrier. The insulation blankets 400 mm wide were placed between the roof purlins and the roof sheets. Z250 purlins were bolted to the supporting angle bars previously welded to the HEB 100 double–tee beams mounted firmly to the test stand. The average thickness of the insulation layer between purlins and sheets measured in the model in the vicinity of fasteners joining the sheets with purlins was close to zero. The thickness of the insulation layer in the middle of the distance between fasteners amounted 6 mm.

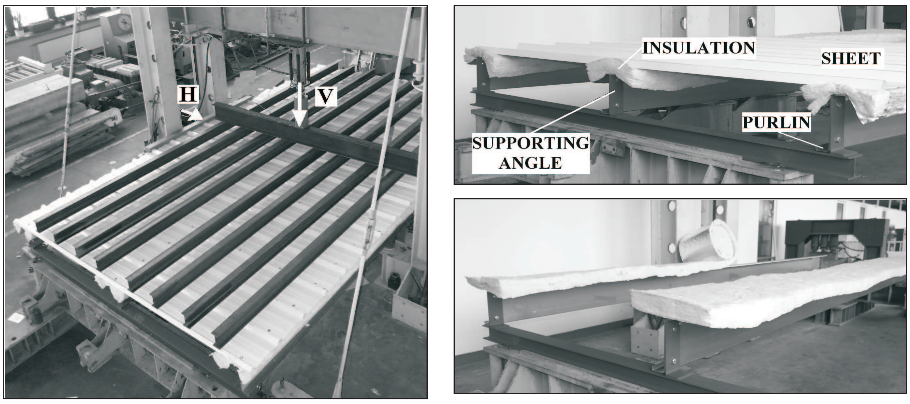

Figure 1 Test model on stand in the Institute of Building Materials and Structures (CUT)

Eight samples (Fig.2a) of the thermal insulation were carried out to describe its material properties under compression according to [8]. The obtained test results shown in Fig. 2b were used to model the insulation properties in the numerical FEM model.

2.2. *Loading procedure*

The research model was subjected to external loads acting in two different directions: vertical and horizontal as it is shown in Fig. 1 and Fig. 3.

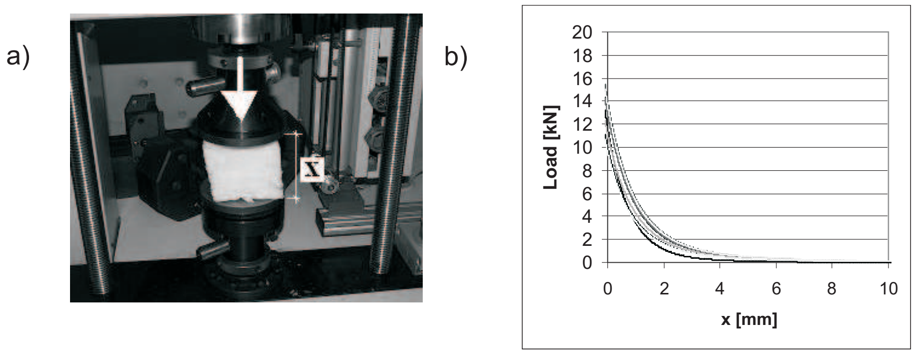

Figure 2 Test of the insulation layer under compression:
a) test of 8 samples (100 x100 x 100 mm) of the thermal insulation under compression,
b) results of the tests

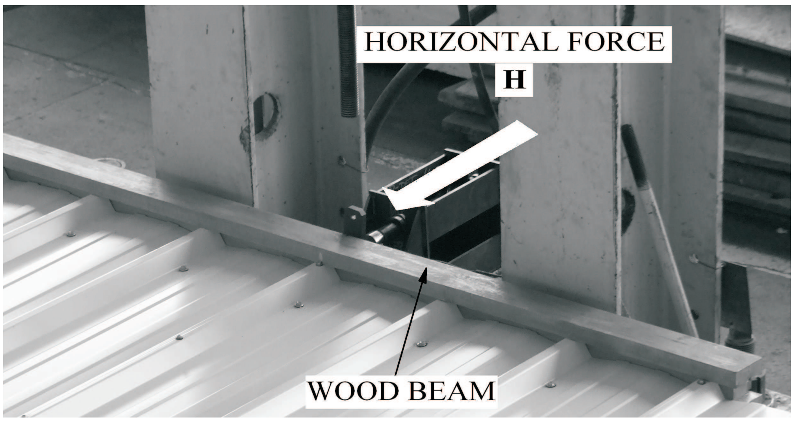

Figure 3 Application of horizontal loading

The vertical load V created by means of a hydraulic actuator was transferred to a IPE 240 steel transversal girder 3.0 m long and then by means of 8 beams IPE 140 each 6.0 m long to the tested sheets.

The horizontal load H also created with use of a hydraulic actuator was transferred to a channel beam made from hard wood (Fig. 3) 2.0 m long and then to the edge of the sheet in the test model. The load was applied to the model in accordance with the A4 annex to EN 1993–1–3: 2004 standard recommendations for tested sheets i.e. in four loading stages (Figs 8, 9 depicted on the paths of equilibrium). During the first stage the research model underwent preliminary tests (V_1 = 33 kN, H_1 = 2.4 kN) then acceptance tests (V_2 = 38 kN, H_2 = 2.9 kN), strength tests (V_3 = 43 kN, H_3 = 3.5 kN) and eventually failure tests (V_4 = 59 kN, H_4 = 5 kN). The horizontal loads H_i were ca 1/10 the loads V_i (without the dead load of the equipment and the model itself i.e. 9.4 kN altogether).

2.3. *Scope of tests*

The following measurements were carried out in the tests:

- deflections of the purlins in the middle of their lengths in points A, E, K, S and at the supports in points C, D, F, G, L, M (Fig. 4)
- horizontal displacements of the bottom flange of the internal purlin in the middle of its span in points B, Q (Fig. 4)
- deflections of the trapezoid sheet in points I, J, N, W i.e. in the middle of the cross sections along the purlin in one (right) sheet span (Fig. 4)
- strains in T1 and T2 (flanges) as well as R3 (web) of the inner purlin in the middle of its span and in the trapezoid sheet at R5 indirect footing as well as in the point of the maximum deflection in the middle of the model span R4 (Fig. 5).

The displacements were measured by means of dial (empty dots in Fig. 4) and induction (full dots in Fig. 4) gauges. The strain measurement was carried out by means of a single resistance strain gauge (T1, T2 in Fig. 5) and rectangular rosettes (R3, R4, R5 in Fig. 5).

3. Numerical model

The numerical calculations were carried out with use of the MSC.Marc program [5,6]. The calibration of the model (Fig. 6) was done on the basis of the experience of previous studies [7]. Both the purlins and trapezoidal sheets were modelled with use of 4 node shell finite elements (number 139 – see [6]) whereas 8 nodes brick elements (number 4 – see[6]) were used to describe the mechanical behavior of the insulation blankets. It is to be noted that in such a structure a direct mutual contact phenomenon between sheet and purlins does not exist. The contact takes place only in a localized zone (lowest trapezoid waves of sheet roof) and through the insulation blankets. So appropriate contact conditions were defined and the zones of interaction between the sheets and the insulation were pointed as well as the ones between the insulation and the purlins. Moreover the pre-compression stresses were introduced to map initial squeeze of the insulation volume due to mounting the roof sheets to the purlins with use of self-driving screws. The screws were modelled using connection elements which allow to join a finite element not only in the nodes of the finite element mesh. This option facilitates the meshing and modelling process. Only one half of the structure was modelled because of the symmetry of kinematic boundary conditions and of the symmetry of loads. The vertical loading was rea–lized in 76 zones of equal pressure forces situated on the highest trapezoid waves of sheet roof surfaces where contact with I profiles occurred. Remaining loads (i.e. the gravity and the horizontal forces) were introduced directly.

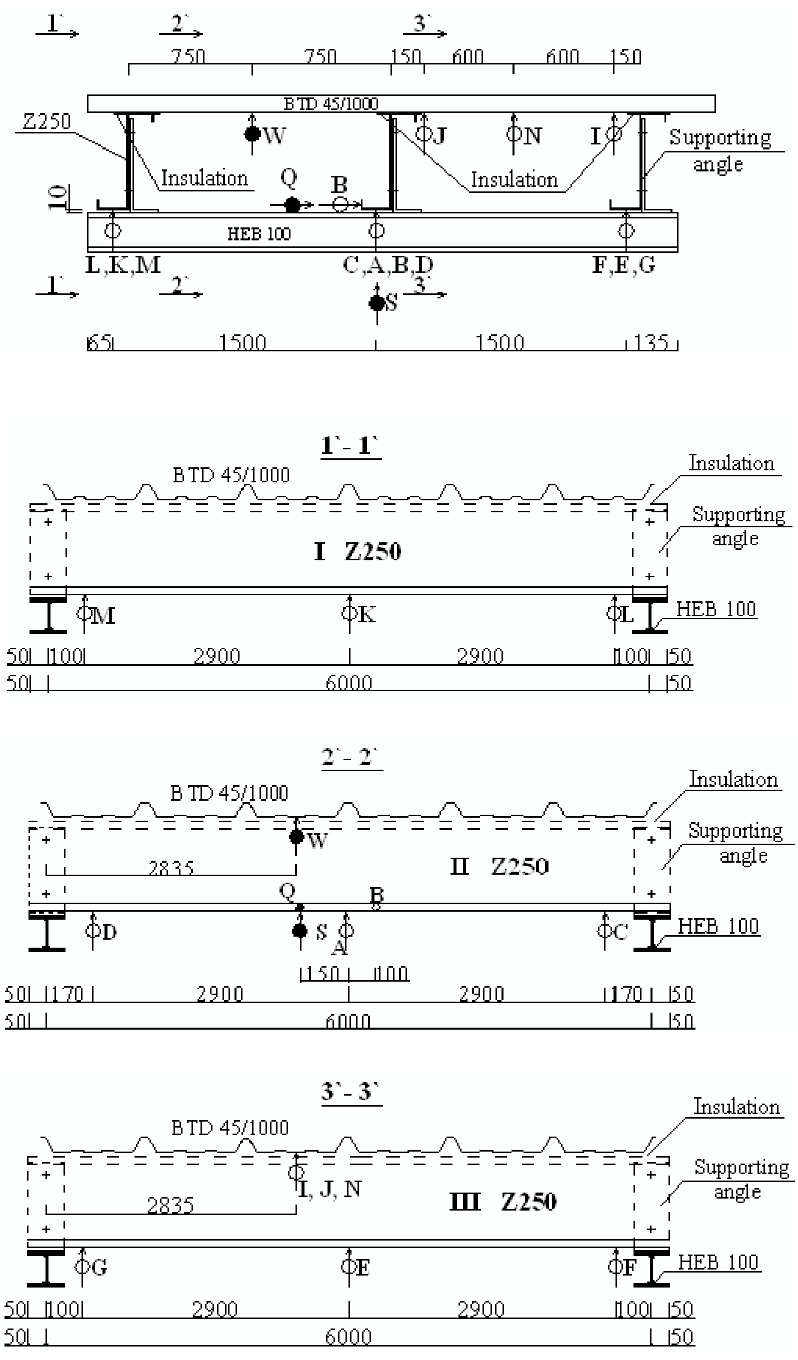

Figure 4 Measurement of deflections

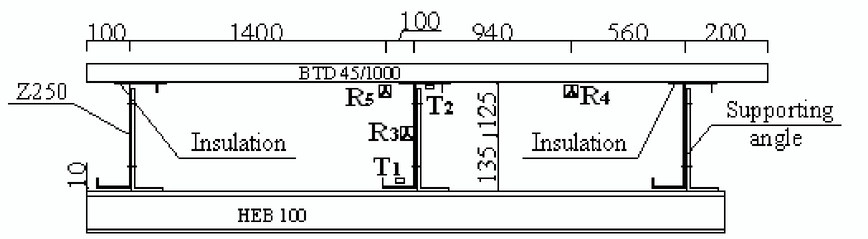

Figure 5 Strain measurement

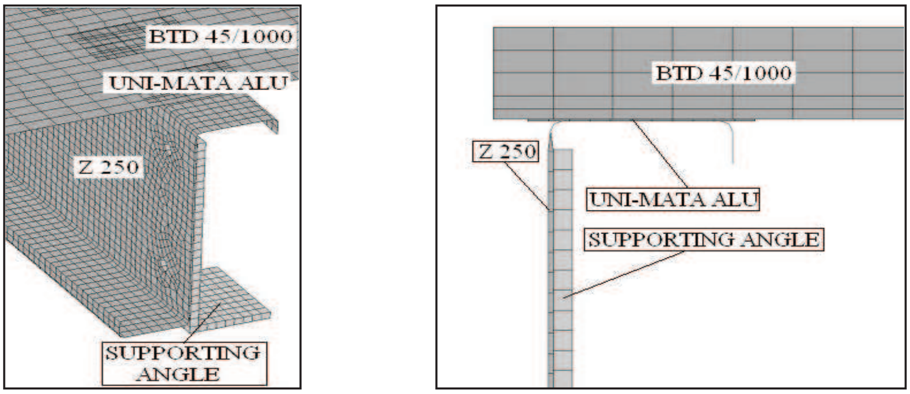

Figure 6 Numerical model

The following assumptions were taken into account during the numerical analysis: the material properties of steel taken as mean values from tests for true elements (for Z250 R_e = 382 MPa, for sheet R_e = 322 MPa), an elastic–plastic model with strain–hardening of steel material (E = 210 GPa, E_t = E/10000), material and geometrical nonlinearity. The steering quantities were the external vertical V_i and horizontal H_i loads whereas the measured values were: the vertical displacements in the points N, W (the middle of the span of the sheet) and A, S (the middle of the span of the internal purlin), the horizontal displacement in the point B, Q, stresses in the purlins and sheets.

4. Results and conclusions

During the tests the following quantities were measured among others: the deflection in point A and the horizontal displacement of the bottom flange in the point B of the internal purlin in the middle of its span. These results are presented in Fig. 7. The shape of displacement after the experiments stays in a good adequacy with the numerical results however their maximal values are considerably higher in the test (Fig. 7) because of greater true imperfections than assumed in the FEM simulation.

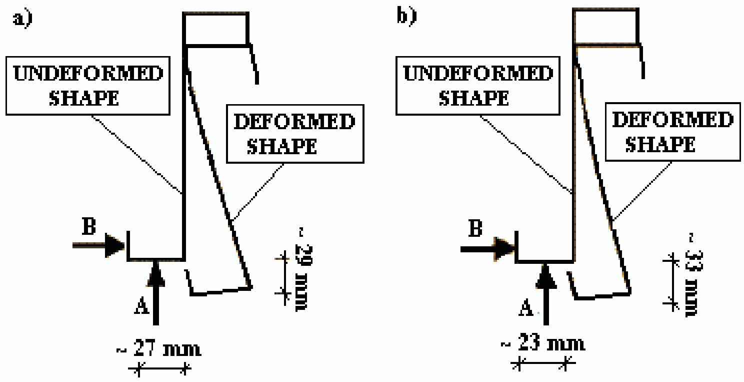

Figure 7 Displacements in points A and B: a) experimental results, b) numerical results

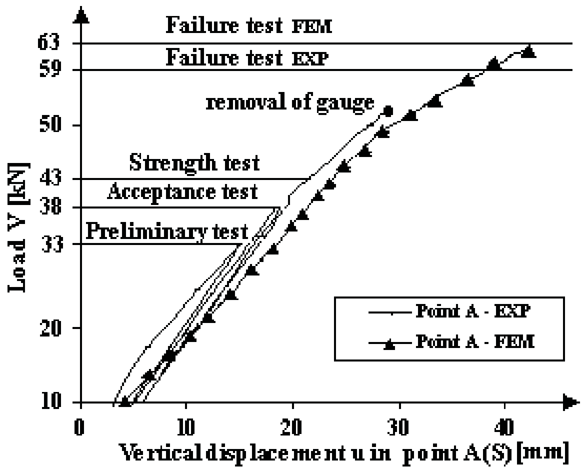

Figure 8 Paths of equilibrium V–u for the internal purlin in point A (S)

The comparison of the experimental and numerical paths of equilibrium V–u (the vertical force – the vertical deflection) for the internal purlin in the point A (S) are depicted in Fig. 8 and for the trapezoid sheet in the point W (N) in Fig. 9.

The value of the load V at failure in the test was 59 kN whereas by MSC. Marc 63 kN (one cycle of loading). The mode of failure obtained in the numerical analysis (Fig. 10) is similar to the mode for the experimental model (Fig. 11). The stresses in the numerical model at the time of failure are shown in Fig. 12. The maximum values of reduced stresses were as follows:

for the sheet in points R4 max $\sigma_{red} = 75$ MPa (max $\sigma_{red} = 66$ MPa),
R5 max $\sigma_{red} = 35$ MPa (max $\sigma_{red} = 41$ MPa)
and for the internal purlin in points R3 max $\sigma_{red} = 62$ MPa
(max $\sigma_{red} = 51$ MPa),

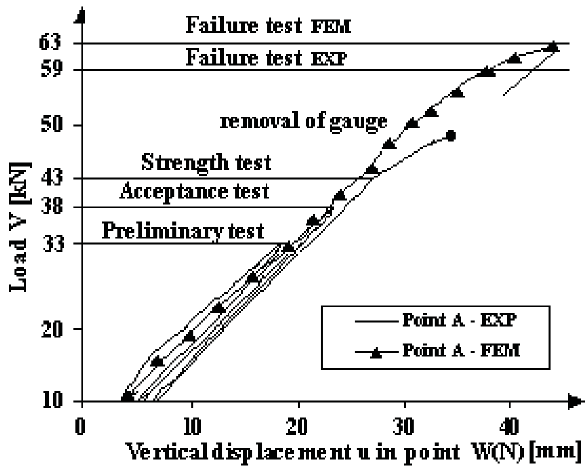

Figure 9 Paths of equilibrium V-u for the sheet in point W (N)

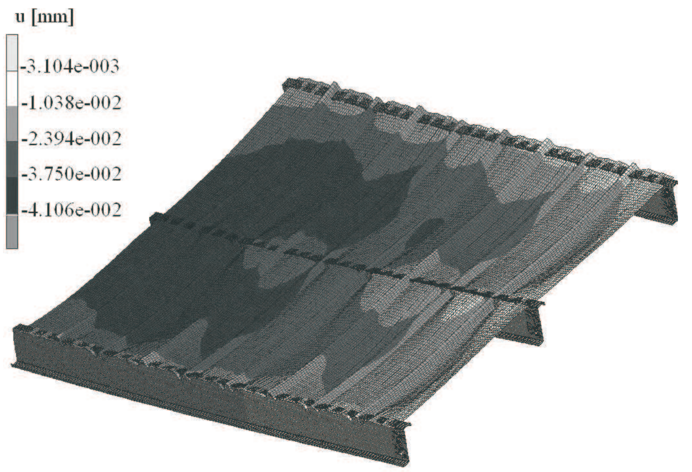

Figure 10 The mode of failure for the numerical model

T1 max $\sigma_{red} = 262$ MPa (max $\sigma_{red} = 230$ MPa),

T2 max $\sigma_{red} = 231$ MPa (max $\sigma_{red} = 207$ MPa). The mean values of the reduced stresses measured in the experimental model are given in brackets for comparison.

The numerical results showed that the analysed beam-sheet structure may be effectively modelled as a whole with use of shell finite elements for steel profiles and sheet roof and brick elements for insulation blankets. The elaborated FEM model of a roof covering is appropriate for simulating the behavior of a true structure of the type.

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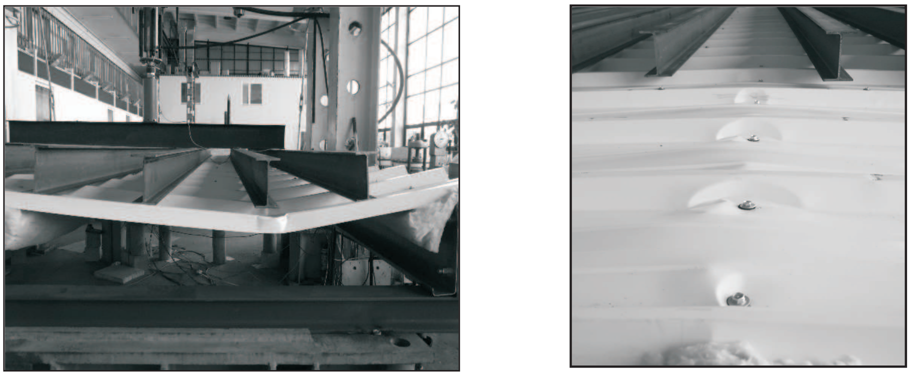

Figure 11 The mode of failure for the experimental model: a) span, b) support

Figure 12 Reduced stress (Mises)

References

[1] **Ye, Z.M., Kettle, R. and Li, L.Y.**: Stress analysis of cold–formed zed–purlins partially restrained by steel sheeting, *Computer and Structures*, 82, 731–739, **2004**.

[2] **Piekarczyk, M.**: Taking advantage of post–buckling strength in designing of steel structures, Monograph No. 299, Cracow. CUT.

[3] **Li, L.Y.**: Lateral–torsional buckling of cold–formed zed–purlins partial–laterally restrained by metal sheeting, *Thin–Walled Structures*, 42, 955–1011, **2004**.

[4] **Jiang, C. and Davies, J.M.**: Design of thin–walled purlins for distortional buckling, *Thin–Walled Structures,* vol.29, 1–4, 189202, **1997**.

[5] MSC.MARC v2008r1. Theory. MARC Analysis Reasearch Corp., USA, **2008**.

[6] MSC.MARC v2008r1. Element Library. MARC Analysis Reasearch Corp., USA,**2008**.

[7] **Pięciorak, E. and Piekarczyk, M.**: Analysis of the post–buckling behavior of a purlin built from thin–walled cold–formed profile, *Thin–Walled Structures*, 45, 916–920, **2007**.

[8] PN-EN 826:1998 Thermal insulating products for building applications. Determination of compression behavior.