Experimental tests of second generation trapezoidal sheets

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ABSTRACT: This paper presents results of experimental tests of second generation trapezoidal sheets of various heights and thicknesses. The presented research program and test stand were prepared in order to meet the assumptions of the calculation model and to eliminate additional unfavourable factors influencing the ultimate bearing capacity. A series of tests of trapezoidal sheets of various heights (135 and 153 mm) and of various thicknesses - 3 thicknesses for each type of sheet, was carried out. In total, 12 sheets were tested - 2 samples of each thickness. The results of the experimental tests were used to verify the numerical FEM model, which in turn will be used to carry out a dozen of parametric analyses necessary for the process of optimizing the geometry of the troughed sheet as the final task. The conclusions turned out to be promising and therefore the created model can be used in planned parametric analyses.

1 INTRODUCTION

Advanced manufacturing technologies and anti-corrosion protections made cold-formed, thin-walled steel profiles widely used in modern building structures. Use of thin sheets brings considerable benefits, such as lower material consumption, although it also can cause some difficulties. This type of structure is sensitive to initial geometrical imperfections and has tendency to local instability, especially in conjunction with global loss of stability. Therefore, the issue of local stability of cold-formed, thin-walled profiles has become the subject of scientific and technical research. Trapezoidal sheets are currently the most popular material used for light cladding of walls and roofs of halls and are used in many applications in general and industrial construction, as well as road and bridge construction. They are widely used as permanent formwork in the composite steel-concrete ceilings (GRISPE PLUS, 2018) and as a part of steel-soil composite structures in road culverts. Troughed sheets can function as self-supporting hall structures (Piekarczuk 2013). They can also stabilize structural elements (Rzeszut & Chwiałkowska 2014), (Sokół 1996). The demand for this type of product in industry is therefore considerable. On the other hand, the manufacturers try to optimize production costs and cross-section geometry (steel consumption) in fierce competition. Various shapes and sizes of trapezoidal steel sheeting are available, their thickness usually varies from 0.5 mm to 1.5 mm. However, the producers are still searching for new solutions in order to improve their products. Hence, the optimization problem is still valid and that is the reason for interest in that issue. The authors of this paper already made some initial analyses to determine the optimal cross-section of the above discussed element. Those works brought some conclusions which will be useful in more complex analyses and gave some general idea how modification of the particular walls of the cross-section affects its efficiency (Rzeszut & Szumigała 2019). The research has been continued by preparing advanced numerical model and conducting physical experiment. The results of the test were used to verify both Eurocode methods (Pięciorak & Piekarczyk 2012) and numerical analyses. Subsequently, the FEM model will be used for parametric analyses, essential for geometry optimisation of the trapezoidal sheet, which is the main objective.

2 DESCRIPTION OF TEST STAND AND PROGRAM

Carrying out physical experiments for each of the postulated trapezoidal sheet geometry is too expensive and practically difficult to implement. The optimization of the cross-section is often associated with the minimization of the thickness of the sheet what causes that the load capacity is usually determined by the local loss of stability. Local buckling is a random phenomenon and strongly depends on initial geometrical imperfections. In order to obtain the real load-bearing capacity of such sheets by means of a physical experiment, many tests must be carried out and the results statistically analysed. It is not possible. The solution of this problem is to conduct a series of numerical and parametric analyses instead of laboratory tests. However, the numerical model used for these analyses should be experimentally verified. The presented experimental studies serve this purpose. It was decided to verify the numerical model only for the simple case of pure bending, neglecting the transverse forces that may affect the bearing capacity of the compressed (crippled) webs on the supports and at the point of the load application. The examination of the conventional case of “pure bending” was difficult to implement in practice, therefore the classic case of four-point bending, i.e. two concentrated forces in the span, spaced at $1/3$ of the span length, was used. The stand available in the laboratory allowed to test elements with typical spans and such a length of sheets was assumed, namely 6 m. The width of the element was equal to the standard width of the given type of sheet, e.g. 882 mm. The scheme of the stand is shown in Figure 1.

The introduction of the external load in the form of two concentrated forces required the use of an additional intermediate structure to convert one force from the piston actuator into two forces transferred to the tested trapezoidal sheet. Initially, it was a wide-flange beam (H-section), which failed the first test. After the pilot tests of the first sheet, it was found that the existing test stand is unsuitable due to the highly dynamic nature of the failure mode. The testing process could turn out to be dangerous both for the valuable measuring apparatus and for the laboratory staff. Also, the uniformity of the linear load distribution was questionable due to the high flexibility of the plates and the low stiffness of the linear element transferring the load.

The stiffness of this element together with the timber blocks was insufficient and it was difficult to regard the load as linear and uniformly distributed. Therefore, another method of imposing almost uniform load was searched for. It was decided to replace single H-section with a special horizontal frame made of rectangular hollow sections. This element should be quite light and simultaneously rigid so that the initial loading of the sheet with auxiliary elements is not too significant in relation to the load capacity. A solution was chosen as it is shown in Figure 2 and after carrying out computational analyses taking into account the compliance of the sheet, it turned out that the load distribution is linear and uniform.

Linear loads should be applied to the tested sheet in such a way as not to cause local crippling of the webs and thus distorting the bending resistance. Similar situation occurred at the supports zone. It was decided to suspend the sheet at the supports, which means, support it only in the upper flanges in each fold and the load apply only in the lower flange (GRISPE 2015). For this purpose, special timber blocks adapted to the dimensions of the sheets were prepared. Those elements located on the supports are based on a special movable, hinge

Figure 1. The experimental stand and scheme.

Figure 2. Modified laboratory stand.

support structure. On the elements located in the place of the applied load, special flat bars with welded round bars are placed in order to precisely locate the load. On the flat bars the above-mentioned frame transferring the load from the actuator is set. Due to the dynamic nature of the experiment, all elements were connected, as shown in Figure 3. A single trapezoidal sheet has a tendency to deformation of the cross-section (distortional deformation), which does not occur in real constructions, as the adjacent plates block this possibility. Hence, there was a need to ensure similar conditions and fasten the plates from below both at the supports and at the place of load application, as shown in Figure 4.

The performed numerical analyses showed that the experiment should introduce displacement control in order to observe the maximum value on the static equilibrium path, i.e. the load capacity of the element. Therefore, in the physical experiment, the force was introduced by creating a displacement. The view of the research stand with the tested element is shown in Figure 4. The tests were carried out until the slab was destroyed. The mode of failure is presented Figure 5.

During the test cycle, an automatic and continuous reading of the force and displacement was performed ("Catman" system) at selected points (Figure 2). The displacements were measured with inductive sensors (Figures 3, 5) positioned in the centre of the span and at the point of direct application of the forces. A professional dynamometer was used to measure the force exerted by the hydraulic cylinder.

Figure 3. The supporting elements.

Figure 4. View of the test stand and transverse ties (stabilizing the sheet).

Figure 5. Failure modes.

3 RESULTS OF THE PHYSICAL EXPERIMENT

Information concerning the parameters of the material of the sheet was necessary to enable verification of the numerical model by the results of the physical experiment. For this purpose, material coupon tests were also carried out. Samples for the standard steel tensile test were prepared (cut using a stream of water) - Figure 6.

The samples were cut from different places of the cross-section of the sheet (flanges and webs). In order to avoid distortions of the results caused by the mechanical cutting process (overheating), it was decided to cut samples from the metal sheets with a water stream under high pressure. Before the test, the samples were carefully inventoried in terms of dimensions and it turned out that the declared thicknesses of the sheets are only a standard designation, and the actual thickness of the sheets is smaller according to the acceptable deviation. It was a very important observation from the point of view of the accuracy of geometrical data entered into numerical analyses. The samples were placed in the jaws of an “Instron” testing machine (Figure 6), an extensometer was mounted and the tests were carried out in accordance with the procedures, and the results obtained during the examination with the “Catman” software are presented in Figure 7.

4 COMPARISON OF THE RESULTS OF THE PHYSICAL AND NUMERICAL EXPERIMENT

A numerical model was prepared in the Abaqus system. The trapezoidal sheet was modelled with shell elements. The load was assumed in accordance with the experimental model, i.e. it was located in the lower part of the fold as a vertical extortion. The model includes also transverse ties (bracing elements). The support conditions were applied to the top of the folds as it

Figure 6. Standard tensile test of steel and samples.

Figure 7. Stress-strain graph for steel sheets based on the experiment.

was in the tested model. The calculations were initially carried out in the Standard procedure using the Newton-Raphson incremental method. In the calculations using this method, it was not possible to unequivocally observe the maximum for the load-displacement static equilibrium path, despite the use of nonlinear procedures. Therefore, it was decided to use a different computational approach consisting of explicit integration method to solve equations of motion and the Explicit procedure to model the dynamic phenomenon (such was the nature of the failure of the sheet). The advantage of this method is that there is no need to look for convergence what is important for large deformations.

After numerous attempts, a numerical model was built. The actual sheet geometry and the measured mechanical properties of the steel were introduced, the parameters of the procedure were selected so that finally the results obtained were sufficiently consistent in terms of stiffness with the results of the experiment (Figure 8).

The Abaqus\Explicit procedure for explicit integration of the kinematic equations of motion does not require the search for convergence in each iteration step and allows to better describe the behaviour of the plates (cross-sectional walls) in the experiment, and even to obtain similar forms of deformation at failure (Figure 9).

Figure 8. Comparison of results of experiment and numerical analyses.

Figure 9. Similar failure modes in numerical analysis and physical experiment.

5 CONCLUSIONS

Based on the physical experiment of trapezoidal sheets, it can be concluded that the prepared numerical FEM model using the Explicit procedure is effective and it can be considered that it has been sufficiently verified in order to conduct further parametric analyses, which are necessary in the next part of the work consisting of conducting optimization analyses of the geometry of trapezoidal sheets (Rzeszut & Szumigala 2019). Due to appropriately selected

boundary conditions, both in the physical and numerical model, it was possible to eliminate additional effects consisting of the crippling of the webs, which could have had an impact on the results. Another problem to solve is establishing a parameter that measures the quality of optimization.

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