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Numerical investigation into plastic hinge formation in arched corrugated thin-walled profiles

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ABSTRACT

The paper concerns thin-walled corrugated steel profiles used as arched roofing in architectural structures. Corrugation formed on the profile surface when the profiles are shaped affects their rigidity and load capacity. The complicated geometry of a profile surface prevents the creation of an analytical description based on the thin film theory. A loss of stability in this kind of profile is related to the formation of local instabilities in the early stage of local plastic mechanisms development. To that end, it is more relevant to identify the lower limit of load capacity to estimate the overall load capacity of the profile. The results obtained by the numerical calculations demand a thorough analysis of the map of strain, which is difficult because there are no clear quantitative criteria describing the beginning of plasticisation formation. The paper presents a method of analysing the results of numerical calculations based on the identification of a perturbation component of displacement in selected points of the profile. The method is based on a discrete Fourier transform and allows the establishment of an estimation criterion for the lower limit of a profile's load capacity.

1. Introduction

Profiled steel sheets in an arc shape are used as roof covers in architectural structures. They are cheap and quick to mount. Elements of the roof covers are manufactured by cold-rolling using mobile rolling mills. The manufacturing process involves the shaping of a trapezoidal profile from a 0.75–1.5 mm thick steel sheet (shape and dimensions as in Fig. 1a) followed by the curving of the previously made profile to form a circular arc with a 6–30 m radius. This way, a single curved profile with corrugated and wavy web surfaces is formed (Fig. 1b).

Single profiles are combined by crimping free edges to form a continuous trapezoidal surface. An arc-shaped surface formed in this way and supported on its two extreme edges is a self-supporting element, which does not require a supporting sub-structure. The installation of a ready-made profile set as roofing on a building construction is presented in Fig. 1c.

A roof cover is exposed to environmental (snow, wind) and process loads [1]. The design of an arc-shaped roof cover should meet the requirements of load capacity and serviceability. Unfortunately, nowadays there are no uniform design methods for such elements, as reference standards do not cover profiles with corrugated surfaces. This kind of roof cover has become popular due to its low manufacturing costs and quick installation. Previously, the dimensioning of roof covers of formed steel sheets was based on computational methods developed by each designer on their own, using simple rod models, which did not take into consideration the corrugated surfaces of a profile. Excess simplification often resulted in misevaluation of the load capacity and, consequently, in structural failures or even the collapse of arc-shaped roofs. Some clarifications to the rod model were proposed in a study by Zaras et al. [2], where load capacity was evaluated by a non-linear model with an orthotrophy impact caused by crosswise corrugation of the profile. This calculation method turned out to be effective in terms of overall load capacity assessment but it did not consider local effects. The paper by Norman et al. [3] describes a corrugated structure introducing some generalisations related to the orthotrophy of the elements and the relation between local and overall loss of stability, but the description applied to a single corrugated element cannot be applied directly to an analysis of corrugated profiles.

The complicated geometry of the profiles of the analysed structures is the major problem in identifying their load capacity and stability. Following the formation of the required curve of the profiles, their surfaces become corrugated and wavy (Fig. 1b). Overpressing on the web surface is quite regular, while the shape of the flange surface mainly depends on the arc-bending radius and thickness of the rolled sheet. The wide variety of sheet thickness and bending radius combinations translates to an inordinate amount of overpressing geometries,

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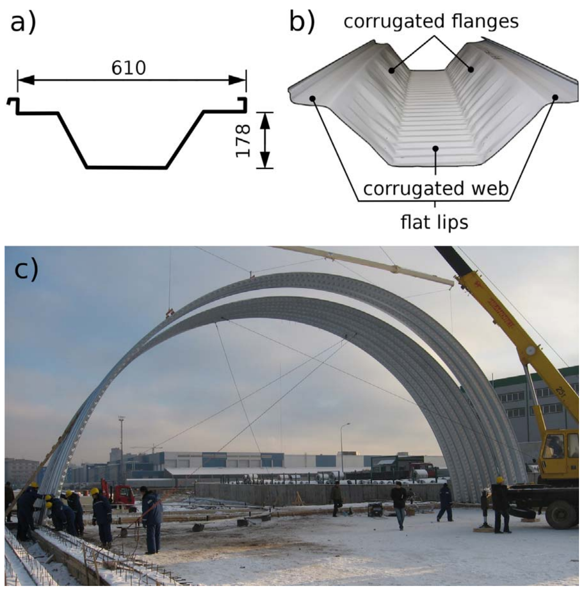

Fig. 1. Tray section a) cross-section, b) surface c) arched roofing under construction [29].

which makes it impossible for a uniform mathematical description to be applied in practice for such a surface.

The global buckling and local plastic mechanisms of thin-walled elements has been the subject of numerous original studies [4–8], but it is still difficult to develop a universal description of local instability for thin-walled profiles with corrugated surfaces. The problems of load-capacity and the rigidity of corrugated profiles have been mentioned in studies and experimental papers [9–12]. Based on these, it was concluded that strong non-linearity caused mainly by local instability, as related to the profile's geometry, determines load capacity and, consequently, the stability of the profiles. Papers [9,10] devoted to the issue suggest that the process of local loss of stability begins in the elastic-plastic range of the construction operation. Plasticisation is initiated in a load range, which is hard to identify but strongly depends on the geometry of the curved and corrugated surface of the profile. That is why identification of the course of local plastic joints and, consequently, the application of computational mechanisms resulting from the theory of boundary load capacity of plates and coatings are highly problematic. In a proprietary study [10], the authors made an attempt to select a relevant model of profile geometry that would be useful for an analysis of profile load capacity. The issue was analysed by subsequent iterations of the model's accuracy. Consequently, a separate geometry model was established, which correctly reflected the results of studies but only did so in peak load values. It was decided that this was not sufficient for a detailed analysis of the mechanism of local instability formation. With regard to the above, another study was performed [9] which investigated the fitness of the proprietary model identified in paper [10], compared to the model obtained by 3D scanning. Finally, the concept of improving the proprietary model was given up in favour of the geometry obtained by 3D scanning.

Despite the application of numerical calculation methods to obtain the perfect geometry via 3D scanning, it is only possible to identify the upper estimated limit of load capacity, which determines the final loss of stability, while the lower limit of the range initiating the beginning of plasticisation still remains unclear, and close to the load level at which the plastic limit is reached.

With regard to the above, the authors proposed a non-ambiguous criterion of identifying the lower limit of the state of development of local plastic mechanisms. This criterion is based on the share of the displacement perturbation component in a selected lengthwise section of a profile for which the Fourier transform was used to identify the value.

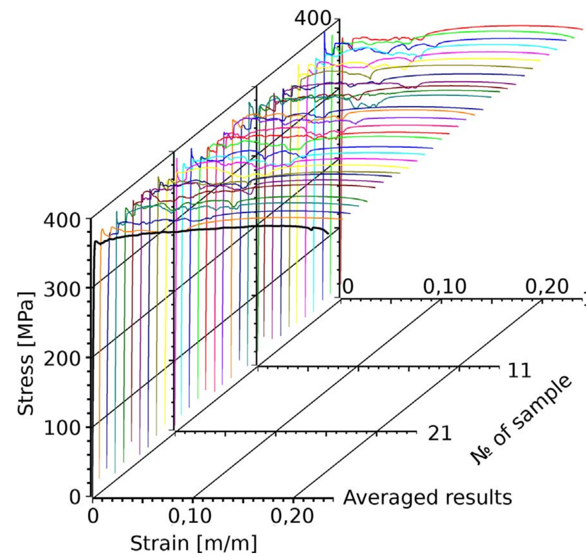

Fig. 2. Tensile test results in terms of ε_{eng} and σ_{eng}.

2. Methodology

2.1. Material stress–strain relationship

The strength characteristics of steel were identified through a series of laboratory tests on 30 samples of steel sheet with a nominal thickness of 1.00 mm (actual thickness: 0.95 mm). A static tensile test performed according to EN-ISO 6892-1 [13], method B, rendered the mean value of yield stress of R_e = 366.3 MPa and tensile strength R_m = 383.6 MPa [9]. The strength characteristics in a static tensile test on steel may vary depending on the strain rate reached during the test. In the static tensile test the strain rate was assumed to be $3{\cdot}10^{-3}$ 1/s. According to the paper by Kotełko [14], when material properties are identified in the tensile test, a load rate within the range of $(10^{-5}–10^{-1})$ 1/s is classified as a static or quasi-static test. The results of the static tensile test are presented in Fig. 2.

An elastic-plastic multi-linear material based on the test results was used for numerical calculations with ANSYS [15]. Based on the parameters obtained in the tests, steel can be classified as S320 GD + AZ grade, according to EN 1993-1-3 [17]. The classification takes into consideration an uncertainty of measurement amounting to 2% of the measured value. Other material constants, such as Young's modulus (E) and Poisson number (ν), were taken according to EN 1993-1-1 [18], and amounted to E = 210 GPa and ν = 0.3 respectively. An isotropic hardening model was acquired for the numerical analysis [15]. The model is suitable for analysis at high loads and assumes that stress equilibrium is achieved as a result of subsequent strain, as hardening grows, while maintaining the plastic surface shape.

The model identifies the relationship between σ_{true} and ε_{ln} variables based on the following formulas:

$$\varepsilon_{ln} = \int_{l_0}^{l} \frac{dl}{l} = ln\left(\frac{l}{l_0}\right) = ln\left(\frac{l_0 + \Delta l}{l_0}\right) = ln\left(1 + \frac{\Delta l}{l_0}\right) = \ln\,(1 + \varepsilon_{eng}) \tag{1}$$

$$\sigma_{true} = \sigma_{eng}(1 + \varepsilon_{eng}) \tag{2}$$

where:

ε_{ln} – relative logarithmic strain,
σ_{true} – true stress,
σ_{eng} – engineering stress (test result),
ε_{eng} – engineering strain (test result),
Δl – sample length gain [mm],
l_0 – initial sample length [mm].

A multi-linear material model adopted for numerical analysis is presented in Fig. 3.