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Research paper

Laboratory testing as a base for numerical modelling of the high-strength hexagonal wire mesh

Michał Grodecki[1], Krzysztof Nowak[2]

Abstract: This paper presents the results of laboratory testing and Finite Element Method (FEM) modelling of high-strength double-twisted steel hexagonal wire mesh used for constructing gabion cages, slope protection systems, rockfall protection barriers. Gabion cages, filled with soil (usually rock particles) are commonly used in civil engineering (for example, in order to form a retaining wall). Static tensile tests of single wire and double-twisted wire were performed. The stiffness and ultimate tensile strength were examined. Special attention was paid to the double-twist behaviour. The unloading tests were also performed and the range of elastic deformation of both single wire and double-twisted wire were determined. The obtained laboratory results (stress–strain relationships for single wire and double-twisted wire) were included in a numerical model of the repeatable cell of mesh (truss model). The simulation in both directions, parallel and perpendicular to the double twist, was performed. On the basis of the obtained load-strain relationship, an anisotropic membrane model for mesh was proposed and calibrated. The obtained value of tensile strength of the mesh (266 kN/m) is much higher than for other meshes known form literature (30–60 kN/m).

Keywords: double-twisted mesh, Finite Element Method (FEM), gabion, numerical modelling

[1]PhD., Eng. , Cracow University of Technology, Civil Engineering Department, 24 Warszawska Str., 31-155 Cracow, Poland, e-mail: mgrode@pk.edu.pl, ORCID: 0000-0003-1554-0555
[2]PhD., Eng. , Cracow University of Technology, Civil Engineering Department, 24 Warszawska Str., 31-155 Cracow, Poland, e-mail: Krzysztof.Nowak@pk.edu.pl, ORCID: 0000-0001-8892-3050

1. Introduction

Steel wire meshes are widely used in civil engineering. One of typical applications is the formation of a box, filled with granular material (usually rock particles), called a gabion. In civil engineering, gabions are often used to form gravity retaining walls (see Fig. 1). Other typical usage of gabions includes riverbeds protection, forming of bridges abutments, slope and landslide protection.

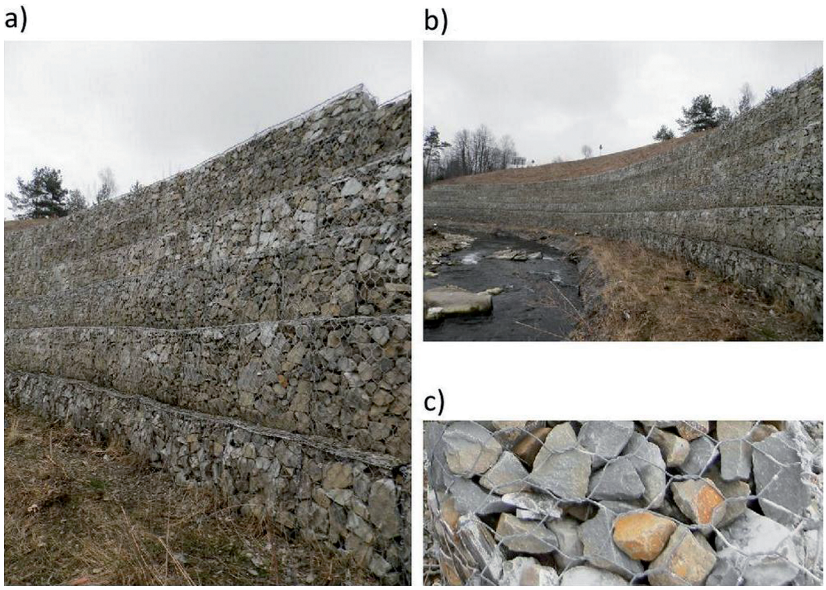


Fig. 1. Gabion retaining wall a), b) whole structure c) close-up on mesh and filling

The behaviour of gabion components should be investigated first in order to describe the engineering behaviour of gabion. The behaviour of high-strength double-twisted hexagonal wire mesh (presented in Fig. 2) is the main goal of the investigation in this paper. According to [1], such mesh is a woven system, produced by twisting a continuous pair of wires three

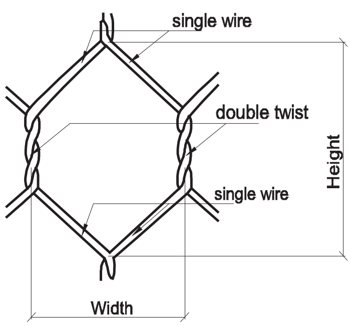


Fig. 2. Basic shape of hexagonal wire mesh

half turns (which forms the so-called double twist). Adjacent wires are then connected to form hexagonal-shape openings. Such hexagonal shape improves the macroscopic mesh strength and stiffness. The double-twist prevents mesh from unravelling due to accidental single wire cutting (for example, due to vandalism). Mesh is usually made from steel with tensile strength of about 500–600 MPa. The subject of the investigation in this paper is a high-strength mesh (produced by "Nector" Company), made from steel with tensile strength of more than 1700 MPa. The chemical composition of a wire rod for the production of such wires is as follows: C%0.77; Mn%0.63; Si%0.22; Cu%0.04; Cr%0.03; Ni%0.019; Mo%0.001; Al%0.001; V%0.001. A mesh cell is 120 mm high and 65 mm wide, the nominal wire diameter is 3.0 mm.

To obtain an innovative product in the form of the first and world's only high-strength hexagonal mesh, it was necessary to develop a new production technology.

The entire process of gabion modelling, which is the scope of this article, is presented in Fig. 3.

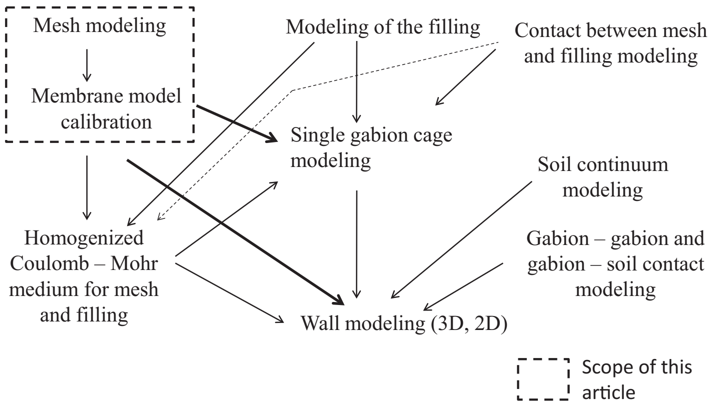


Fig. 3. Scope of this article in the field of gabion modelling

The mesh behaviour could be investigated during laboratory tests or with the use of numerical simulations (both are used in this paper). A typical laboratory test is a static tensile test of a mesh sample described in [2–4]. The results referred to in the literature are very often limited to the ultimate tensile strength of the mesh and the corresponding ultimate strain (elongation) (e.g. [2]), usually without any reference to material properties (Young modulus, plasticity limit and tensile strength) of used steel. More detailed results are presented in [1, 3–6], where force-displacement curves for different meshes are presented together with stress-strain relationships for steel. Observed behaviour of the mesh is far from isotropic, so use of anisotropic models is essential in numerical modelling. Outline of anisotropic models is given in [7]. Mesh-subsoil interaction (a pull-out capacity issue) could also be a subject of interest (see [11]). Single gabion static compression tests (in different loading conditions) are also performed (e.g. [1,5]), numerical models are proposed and calibrated (in [5]). The whole wall could be also tested [1] and modelled [13, 15]. Comparison of analytical and numerical stability calculations results are given in [15].

Punch tests are also commonly used, especially if mesh is used for rockfall protection (examples are given in [1, 16]).

The main source of the complication in the mesh analysis is a double twist: twisted wires are subjected not only to tension (like single wire), but also to bending, torsion and shearing ([18]). However, a simplified "stress" definition used for double wire (normal force divided by the cross-sectional area) is usually used for simplification. In this work nominal (engineering) stresses and strains are used.

Numerical analysis is often used to simulate mesh behaviour during static tensile tests. A numerical model should be calibrated in order to properly replace the laboratory tensile tests results. The force-displacement relationship and ultimate load are subjects of investigation. Examples of such analyses are presented in [1, 6, 18].

Numerical simulations are performed by means of the Finite Element Method (FEM) (e.g. [18, 19]) or the Discrete Element Method (DEM) [1, 3, 5, 6, 12, 16].

Building the numerical model with the use of 3-dimensional continuum elements describing the complex geometry of the structure exactly as it is (especially of the double twist) is very difficult and numerically ineffective (cf. [19]). In general, the behaviour of mesh and its components (single and double wire) is strongly nonlinear and this phenomenon could not be neglected (cf. [18]). Also, the contact problem (friction between wires) is another source of complication (problem of friction between beams is a main topic of [20]). Thus, usually a simplified model (truss model) describing the wire behaviour on the rod level is used. Such model for single wire could be calibrated on the basis of laboratory tensile tests. Laboratory tests can also be conducted for double wire (this approach is used in this article, which allows to consider the effect of contact between wires); however, the alternative approach proposed in [19] (calibrating on the basis of 3-dimensional numerical simulation of the double wire tensile test) could also be used. Similar approach (starting from single and double wire tests in order to obtain full-scale mesh model) is used in [1].

2. Laboratory tests of single wire and double-twisted wire

The tensile tests were performed using a universal testing machine UTS 100K. The range of force application is up to 100 kN. The UTS testing machine confirms class 1 requirements according to EN 10002-2 standard, and also DIN 51120, 51121, 51123, 51127, VDE 0113, BS 1610 Grade A, NF A03-501, ISO-R147, ASTM E4 [21]. The original control unit of UTS and management software were modernized by ZWICK. The force measurement is performed by class 1 Hottinger precision load cell, according to DIN51221 standard. Its accuracy is 0.5% within the range of 1 kN to 100 kN. The extension was measured by a modular sensor arm extensometer of class 1 accuracy according to the EN ISO 9513 [22]. The samples were fastened by wedge clamping jaws.

The material characteristics of the examined material was determined in a quasi-static tensile test according to [23]. The tests were performed in room temperature. The velocity was controlled by movement of the traverse and kept constant on the level of 2%/min.

The tested parameters were the following: the Young modulus, ultimate strength and fracture strain. The Young modulus was examined within a linear range up to 400 MPa.

2.1. Single wire tests

The results were obtained for wire samples of 3 mm diameter and 150 mm length;10 tests were performed. The obtained stress–strain relationship shows very good repeatability (see Fig. 4). The tested material behaves linearly (obeying the Hooke's law) up to about 1000–1200 MPa. For higher stresses a nonlinear behaviour is observed. Tensile strength is almost equal for all tested samples (1721.50 MPa, with a very small deviation of 0.4%). Strain at failure (fracture strain) is between 0.080 and 0.105. Young modulus E (for the linear part of the stress–strain curve) is estimated as 189 MPa, with a deviation of 4%. Strain at failure is much lower than for steel with lower tensile strength (about 0.25, according to [1]). Because of a long non-linear range of stress–strain relationship, the elastic–ideally plastic model for single wire has a limited application to properly describe material behaviour for stresses above 1000–1200 MPa.

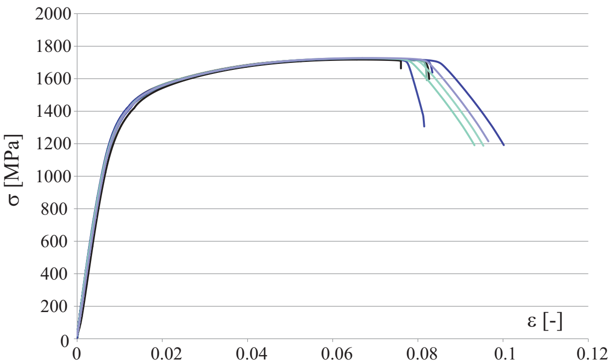


Fig. 4. Stress-strain relationship for single wire, laboratory tests results

The only observed failure mode was necking, which was quite obvious (see Fig. 5).

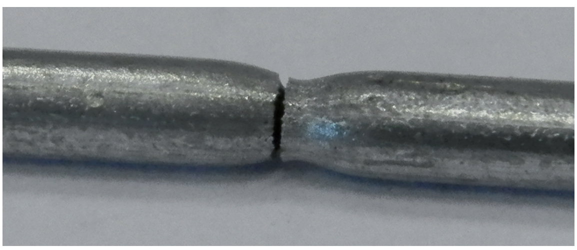


Fig. 5. Single wire after failure, visible necking

Additional loading-unloading tests were performed to judge if a nonlinear behaviour of single wire is of a nonlinear elastic or plastic type. The obtained results show that unloading performed at about 1000 MPa results in some irreversible (plastic) deformation. Unloading from 1400 MPa results in about half of the strain remaining as irreversible. A similar process at 1600 MPa results in about 65% of the strain remaining as irreversible. Thus, a nonlinear behaviour of the tested material is of a plastic type. Hysteresis of the unloading–reloading path is almost invisible and could be neglected in further investigations (see Fig. 6).

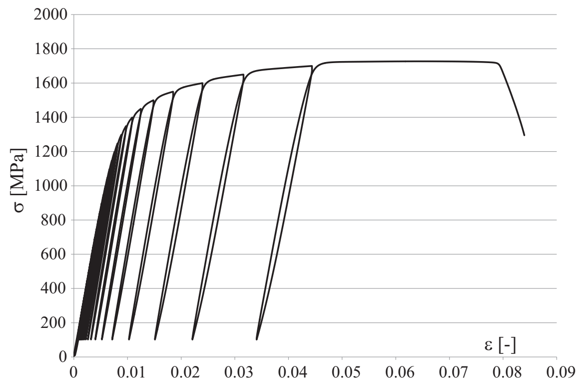


Fig. 6. Stress-strain relationship for single wire, loading–unloading laboratory tests results

2.2. Double-twisted wire tests

Six tests were performed (see Fig. 8). The obtained results show two types of the double-twisted wire behaviour. This is due to two different kinds of double twist (symmetric and non-symmetric), whose behaviour differ to some extent. Those two kinds of double twist are an effect of the production process (weave direction) and appear in the mesh in parallel rows (see Fig. 7).

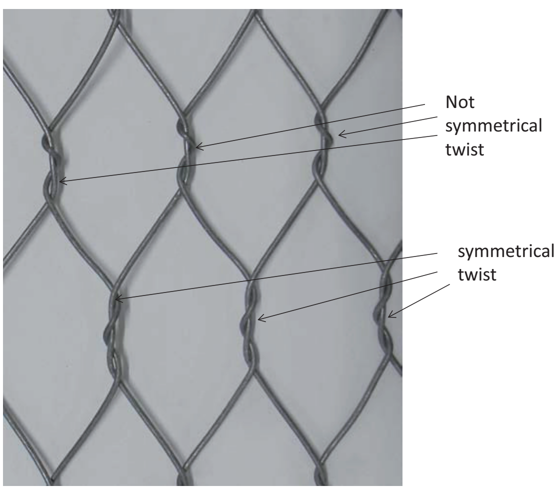


Fig. 7. Symmetrical and not symmetrical double twist

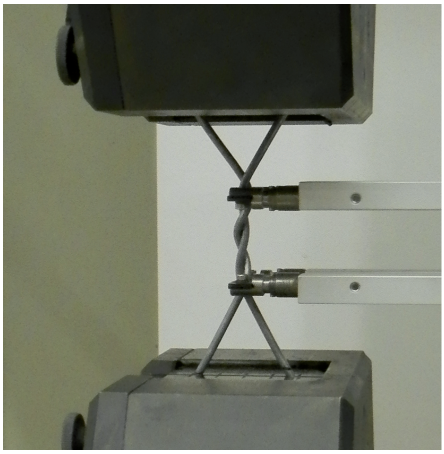


Fig. 8. Double twist during testing

Tensile strength of both kinds of double twist is almost identical, about 1225 MPa, and strain at failure range from 0.045 to 0.055. So tensile strength of the mesh could be estimated (according to [18]) as follows:

$$N = \frac{A \cdot f_t}{w} \tag{2.1}$$

where: A – wire cross-section (14.14 mm^2 for two 3 mm wires), N – ultimate mesh load, w – mesh opening (width) (0.065 m for the tested mesh), f_t – tensile strength of the double wire (1225 MPa).

The obtained value of mesh tensile strength $N = 266$ kN/m is much higher than presented in [1] (where the maximum value was about 57 kN/m). This is due to high tensile strength of the used steel (1721 MPa, in [1] much weaker steel with tensile strength of about 575 MPa was used).

Ratio between tensile strength of the single and double wire is about 1.41, much less than in [1] (2.88) and more than in [3] (almost 1).

A typical failure mode of a double twist is a failure of the wire near the beginning of the double twist (Fig. 9). Wire fails due to shearing, while necking is invisible.

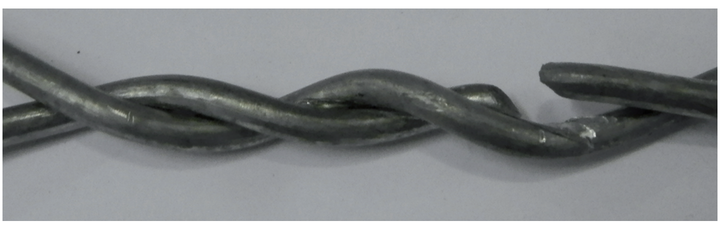


Fig. 9. Double twist after failure

Symmetrical wire behaves almost linearly up to about 800 MPa with average E = 23.2 GPa. For higher stresses some hardening is observed (see Fig. 10). Non-symmetrical wire behaviour is much more non-linear.

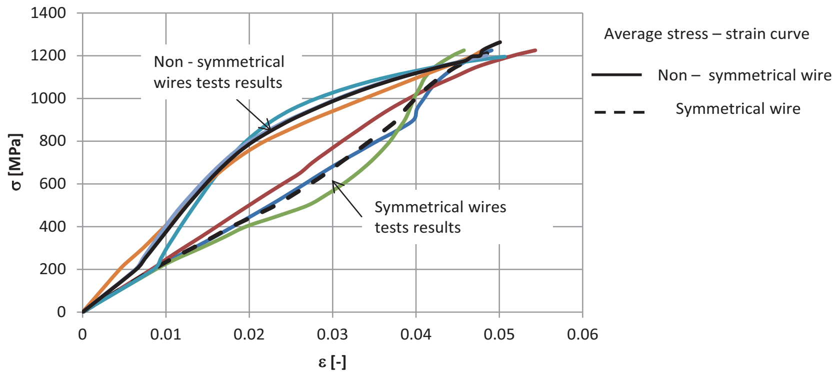


Fig. 10. Stress–strain relationship for double-twisted wire

Secant generalised Young modulus in a 400–800 MPa range for symmetrical wire is about 24 GPa, while for non-symmetrical it is about 40 GPa. This is much less than in case of single wire. This is the effect of the complicated behaviour of double twist (not simple tension, but also bending, shearing and torsion of wires). Double twist works as a construction element and its stiffness depends on the original geometry, e.g. twist tightness.

Additional loading-unloading tests were performed to judge if a nonlinear behaviour of the double twist (especially non-symmetrical one) is of a nonlinear elastic or plastic type. The obtained results show that unloading at about 600 MPa results in about 65% of the strain remaining as irreversible. So, a nonlinear behaviour of the double twisted wire is of an irreversible type. Hysteresis of the unloading–reloading path is small, but a more visible than for single wire (see Fig. 11).

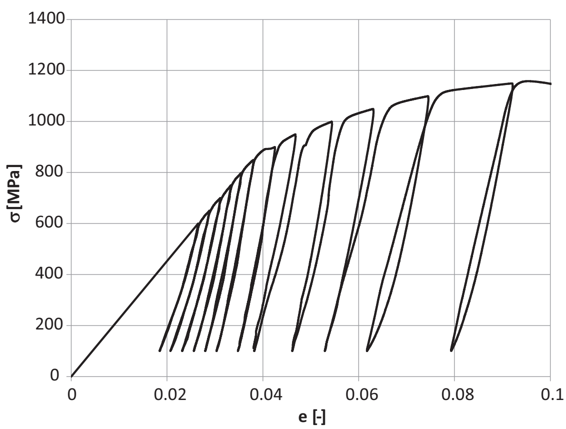


Fig. 11. Stress–strain relationship for double twist, loading–unloading laboratory tests results

3. Repeatable cell of mesh numerical modeling and membrane model calibration

Numerical simulation of the static tensile tests (in the direction parallel and perpendicular to the twist) of the repeatable cell of the mesh was performed. All calculations were performed with use of ZSOIL.PC FEM system, described in details in [24]. The stress–strain relationships for single and double wire (averaged from symmetrical and non–symmetrical wire), obtained from the laboratory test presented before, were used to simulate mesh behaviour (truss model). Then, an anisotropic membrane model with limited tensile strength was calibrated in order to obtain similar load-strain curves. Displacement-driven approach was used.

Failure of the double twist is observed during numerical simulations in both directions. Normal force in single wire at failure is about 11.46 kN (which corresponds to 1621 MPa, 94% of the single wire tensile strength). In double twist normal force at failure is 17.32 kN (which corresponds to 1225 MPa, 100% of the double twist tensile strength). This same normal force distribution at failure is observed in parallel and perpendicular to the twist tensile test simulations (Fig. 12).

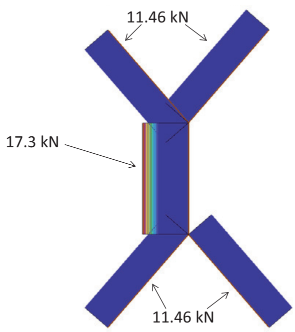


Fig. 12. Normal force distribution at failure, results of numerical simulations (identical in tension parallel and perpendicular to the twist direction)

Anisotropic membrane has only in-plane stiffness and is capable of reproducing anisotropic behaviour of the mesh (both strength and stiffness anisotropy). Such a model has a set of parameters, which need to be calibrated:

K_{xx}, K_{yy} – modulus of the membrane in the X and Y direction [kN/m],

K_{xy} – shear modulus of the membrane [kN/m],

Ft_x, Ft_y – tensile strength of the membrane in the X and Y direction [kN/m],

Fc_x, Fc_y – compressive strength of the membrane in the X and Y direction [kN/m].

Parameters of the anisotropic membrane model interpretation is shown in Fig. 13.

First of all, strength parameters were calibrated. Ft_y was estimated by means of equation (2.1), Ft_x was estimated as an ultimate load of the mesh in the direction perpendicular to the twist (on the basis of the repeatable cell of the mesh truss model), Fc_x and Fc_y were set to 0.

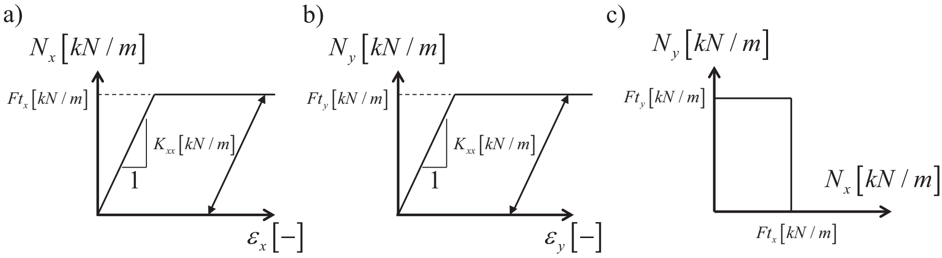


Fig. 13. Anisotropic membrane model. Load – strain relationship a) in the X direction b) in the Y direction and c) plasticity surface

Stiffness parameters K_{xx} and K_{yy} were calibrated in order to properly reproduce the tensile behavior (both in the Y direction parallel to the twist and in the X direction perpendicular to the twist) of the repeatable cell of the mesh (obtained from the truss model) in the membrane model. Minimization of $N_{dev,m}$ was a calibration criterion. K_{xy} was set to 0.

$$N_{dev,m} = \sqrt{\frac{\sum_{i=1}^{n} (N_{rc} - N_m)^2}{n}} \tag{3.1}$$

where: N_{rc} – value of force obtained from repeatable cell model, N_m – value of force obtained from membrane model, n – number of points on load – strain curve.

The repeatable cell of the mesh is presented in Fig. 14 and membrane model in Fig. 15. Membrane model dimensions were 1×1 m, 2500 membrane elements were used. The obtained values of membrane parameters are presented in Table 1.

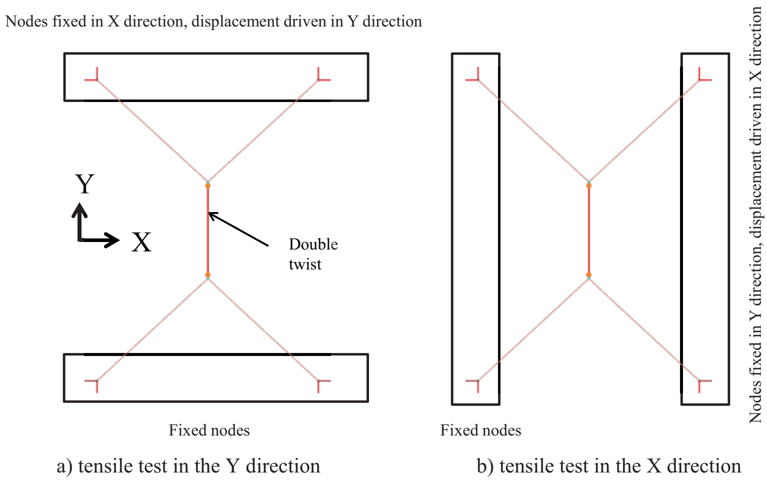


Fig. 14. Repeatable cell of the mesh

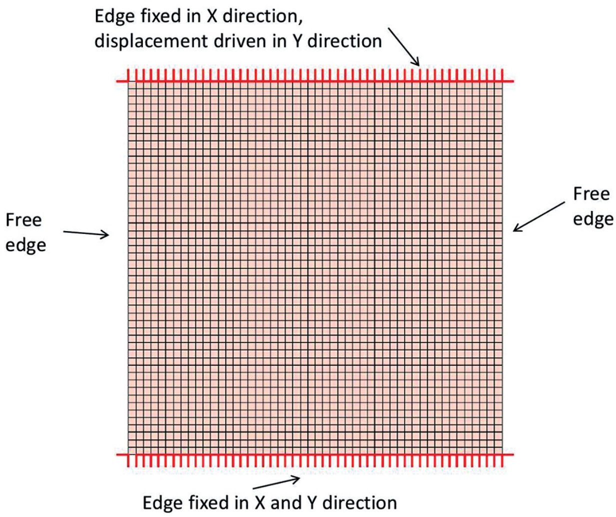
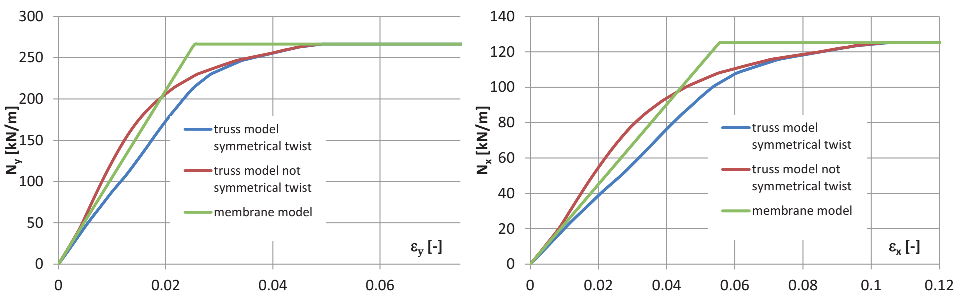


Fig. 15. Membrane model with boundary conditions (tensile tests in the Y direction)

Table 1. Estimated values of membrane model parameters

K_{xx} [kN/m]	K_{yy} [kN/m]	Ft_x [kN/m]	Ft_y [kN/m]
2256	10506	125	266

The load-strain curves obtained by means of the membrane model were compared with those obtained from the truss model of the repeatable cell of the mesh and good agreement was observed (Fig. 16).



a) load in the twist direction

b) load perpendicular to the twist

Fig. 16. Comparison of load–strain curves obtained from the truss model of the repeatable cell of the mesh and the membrane model

Therefore, the membrane model could be used in further research, for example in whole gabion compression test simulations or in whole gabion wall behaviour simulations.

The estimated values of K_{xx}, K_{yy}, Ft_x and Ft_y show that the mesh behaviour is really anisotropic (ratio $K_{yy}/K_{xx} = 4.66$, $Ft_y/Ft_x = 2.13$ – values similar to those presented in [18]).

The obtained values of tensile strength of the mesh are much higher than the values presented in [1] and [18] (30–60 kN/m), due to much higher strength of the single and double wire (about 575 MPa and 200 MPa in [18], 1721.5 MPa and 1225 MPa for the tested material).

4. Conclusions

The above-presented numerical models (truss and membrane) of the wire mesh are useful tools, which properly describe the mesh behaviour in tension conditions. Thus, the membrane model can be used as an element of the whole gabion model (together with an appropriate model of filling and interface between the filling and the mesh). The required data for the model are relatively easy to acquire simple (strain-stress relationship for single wire, double twist and geometry of the mesh). The tested mesh has very high tensile strength (266 kN/m, where for typical mesh tensile strength is about 30–60 kN/m). Strong anisotropy (both in the term of stiffness and strength) is observed ($K_{yy}/K_{xx} = 4.66$, $Ft_y/Ft_x = 2.13$). Observed nonlinear behaviour of the mesh is mainly caused by nonlinear behaviour of the double twist. Two different kinds of double twist (symmetrical and non-symmetrical) were found in the tested mesh and differences in their behaviour were tested in laboratory and included in numerical model of the mesh.

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Badania laboratoryjne jako podstawa modelowania numerycznego sześciokątnej siatki splatanej wysokiej wytrzymałości

Słowa kluczowe: gabion, Metoda Elementów Skończonych (MES), modelowanie numeryczne, siatka splatana

Streszczenie:

Artykuł przedstawia wyniki badań laboratoryjnych i symulacji numerycznych (wykonanych z wykorzystaniem Metody Elementów Skończonych MES) sześciokątnej stalowej siatki splatanej wysokiej wytrzymałości, wykorzystywanej do budowy koszy gabionowych, zabezpieczania skarp oraz konstrukcji zabezpieczeń przed spadającymi odłamkami skał. Kosze gabionowe, wypełnione przez grunt (najczęściej okruchy skały) są powszechnie wykorzystywane w budownictwie (np. do konstrukcji murów oporowych). Zostały wykonane testy statycznego rozciągania pojedynczego drutu i podwójnego splotu, badano sztywność i wytrzymałość testowanego materiału. Specjalną uwagę zwrócono na zachowanie się podwójnego splotu. Wykonano również testy odciążeniowe, określono zakres sprężystej pracy pojedynczego drutu i podwójnego splotu. Uzyskane zależności naprężenie – odkształcenie wykorzystano do zbudowania modelu numerycznego powtarzalnej komórki siatki (model kratownicowy). Wykonano symulacje rozciągania w kierunku wzdłuż i w poprzek podwójnego splotu. Na podstawie uzyskanych zależności obciążenie – odkształcenie wykalibrowano model membrany anizotropowej. Uzyskana wytrzymałość siatki (266 kN/m) jest znacznie większa niż siatek znanych z literatury (30–60 kN/m).

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