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Topology optimization of a junction in a biaxial geogrid under in-isolation tensile loading

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ABSTRACT: The finite element method is a powerful tool that can be used to analyse problems including complex geometries and material properties. In this study, the general-purpose finite element software ABAQUS was used to investigate the load-strain response of a biaxial geogrid under in-isolation tensile loading. A 3D model was developed, accounting for different thickness of geogrid elements and their nonlinear response. Then, TOSCA module was used to investigate an alternative design of a junction profile. The geogrid was submitted to uniaxial and biaxial tensile loading, simulating a wide-width tensile test and a biaxial wide-width tensile test. Validation was performed by comparing the numerical model with experimental data. Optimization results showed that it was possible to reduce the junction volume profile by 53% with a compromise of 3% in maximum bearing capacity.

1 INTRODUCTION

Numerical modeling of the tensile response of geosynthetics can be a challenging task. For geogrids, the complex geometry and the nonlinear response of the polymeric material are the main causes of complexity for numerical implementation. To explore alternative geometry designs, 3D numerical simulations can be used to map the stress distribution within the geogrid elements, aiding to the understanding on how the geogrid works and how it can be improved. In this paper, experimental data was used to calibrate a numerical model of a biaxial geogrid. The objective was to use the validated model to assess a more efficient design for the junction profile of the studied geogrid under tensile loading.

Geogrid reinforcement is an effective method to improve the performance of earth structures by transferring the tensile load from the soil to the reinforcement. Thus, the design of geogrid reinforcements are mainly determined by their tensile resistance. Numerical methods have been developed to model geogrids both in-isolation (Amirhosseini *et al.* 2022) and in soil-geosynthetic applications (Chen *et al.* 2021; Gu *et al.* 2017; Leonardi & Suraci 2022; Perkins 2000; Perkins & Edens 2003; Shen *et al.* 2019; Yang *et al.* 2020). These studies have focused on the general response of the reinforcing elements under various conditions, often recurring to simplified models for the geometry and material properties.

A 3D elasto-plastic finite element (FE) model was studied using the general purpose FE software ABAQUS (2021). The in-isolation tensile response of the geogrid was analysed.

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The model was initially calibrated with experimental data on the machine direction (MD), wide-width tensile test (ISO-10319: 2015). Then, a topology optimization study was carried out to produce an alternative profile for the geogrid junction.

2 CALIBRATION OF THE 3D FEM MODEL

2.1 *Model development*

Geometry and boundary conditions: The geometric details were directly created in ABAQUS considering the 3D solid features of the geogrid. The studied geogrid had a ultimate tensile strength of 40 kN/m for a peak strain of 10% (nominal values for the MD). The cross-section of the longitudinal and transversal ribs were, respectively, 2.5 x 2.2 mm^2 and 2.2 x 1.4 mm^2. The curved junction profile was 5.8 mm thick. The specimen was composed by 5 longitudinal and 5 transversal ribs and had total dimensions of 132 x 132 mm^2 between rib centres (Figure 1). The boundary conditions emulated those of the experimental tensile test. Both ends had translation constraints along the Y direction (perpendicular to the applied force), with one end being fixed along the X direction (parallel to the applied force). The numerical test was carried out by applying a prescribed displacement at the other end of the geogrid model with the same strain rate of 20%/min (0.44 mm/s) used in the experimental test. Only half of the longitudinal bars were modeled utilizing symmetry for enhanced computational performance.

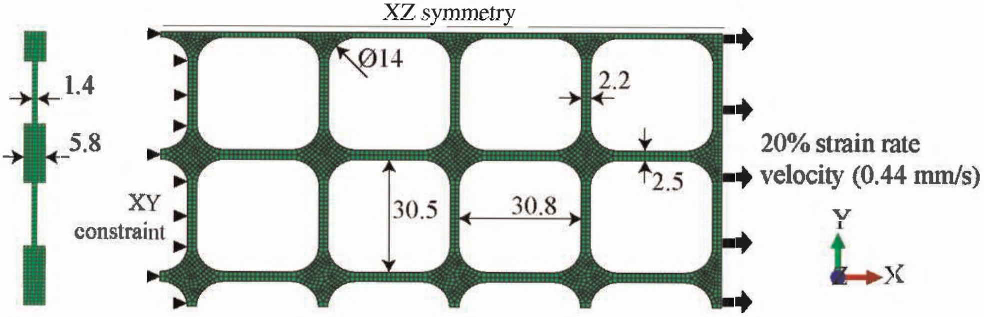

Figure 1. Geometry and boundary conditions of the geogrid. All dimensions are in mm.

Constitutive model: The experimental data available referred to wide-width tensile tests, carried out according to BS EN ISO 10319 (ISO-10319: 2015), which was used to compose a nonlinear elasto-plastic material model. A isotropic material was composed using the experimental data on the MD direction (Figure 2), where T_{max} is the maximum tensile load and e_{max} is the corresponding strain. The experimental load per unit width/strain curve shows a nonlinear behaviour, even for small strains. Default elasto-plastic material with isotropic hardening from ABAQUS was used, with an Young's modulus of 1190 MPa (obtained from the initial tangent response on the MD direction) and a Poisson's ratio taken as 0.3 (Perkins 2000), together with the elastic component deduced from the experimental load-strain response. Stresses and strains were evaluated using a von Mises yield criterion.

2.2 *Stresses and strains in the geogrid*

The modeling results for an axial displacement of 8.7 mm are shown in Figure 3a. This displacement is relative to a 20 s test time under a strain rate of 10%/min where the maximum plasticity occurred. Displacements were linearly distributed along the geogrid, with a null deformation at the left end (where it was constrained) and the maximum displacement at

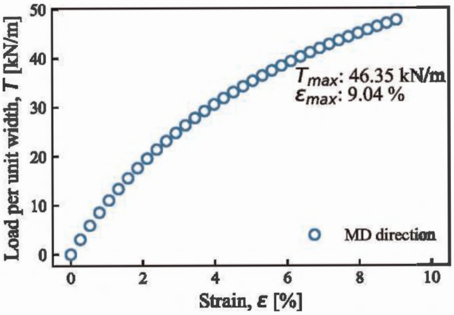

Figure 2. Experimental uniaxial load per unit width/strain curve for the MD direction (EN ISO 10319:2015).

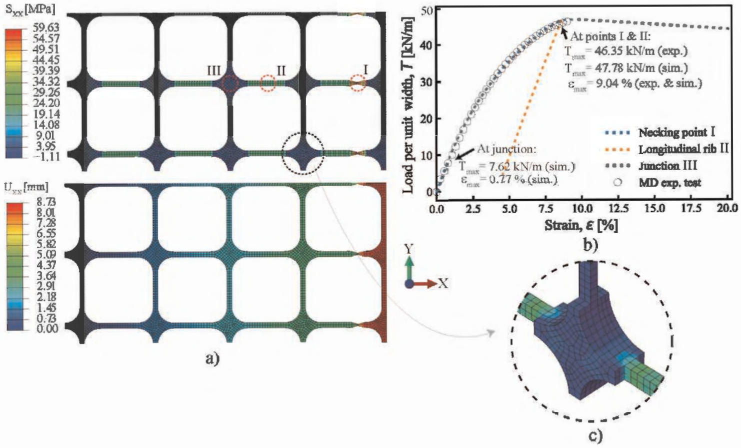

Figure 3. Simulation results for the tensile test simulation: a) stresses and strains at maximum plasticity (8.7 mm displacement) in terms of true stress/strain; b) load per unit width/strain curve of experimental (exp.) data and simulation (sim.) at three points (I, II & III), in terms of nominal stress/strain; c) 3D detail on the stress distribution in the junction.

the right end (where the prescribed displacement was applied). The axial stress plot Sxx showed an equally distributed tension under the longitudinal ribs, whereas the junctions and perpendicular ribs showed significantly less stress concentration. The necking effect spotted at point *I* was in line with experimental tests, where failure at the longitudinal ribs near the clamps often occurs. The load-strain overlay between experimental and numerical tests is shown in Figure 3b. The model was able to accurately reproduce the tensile test with a slight overestimation of the maximum load (3% error), whereas the maximum strain was the same in the physical and in the numerical tests. The results were also in good agreement with the nominal properties reported by the manufacturer. Figure 3c shows a corner junction with the respective critical stresses at maximum plasticity. Specially close to the perpendicular rib, the junction profile had little to no stresses or relative strains.

It is important to notice that the differences in magnitude results between the ABAQUS plots (Figure 3a) and the load per unit width/strain curves (Figure 3b) were due to the fact that ABAQUS results are in terms of true stresses/strains, while traditional tensile tests are reported in terms of nominal (engineering) stresses/strains. For geosynthetics the response is quantified ignoring the thickness of the material (as it can vary with confinement).

3 TOPOLOGY OPTIMIZATION OF A GEOGRID JUNCTION UNDER IN-ISOLATION TENSILE LOAD

3.1 *Model development*

A continuous structure submitted to a topology optimization process can be regarded as a material (volume) distribution problem (Bendsoe & Sigmund 2003; Pang & Fard 2020; Saleem *et al.* 2008). For this particular problem, the optimization target was to find an alternative minimum volume distribution within the boundary constrains for the maximum global stiffness. In ABAQUS, TOSCA module was used to search iteratively for a minimized strain energy (to maximize global stiffness), while taking into the consideration boundary conditions and applied forces for a reduction in volume where stresses are not critical. The goal was to find the optimal volume configuration for the junction profile that saves on material, while still being able to perform the same tensile test.

Model development and boundary conditions: A simplified unit of the geogrid was used to run the TOSCA algorithm for two scenarios: 1) the geogrid was submitted to a axial displacement similar to that of the original tensile test; 2) the geogrid was submitted to a biaxial prescribed displacement, in order to explore the optimization results. Since a prescribed displacement was applied (velocity), the strain energy was set to be maximized, while the volume constraint was set to be less or equal to 50% than that of the initial value. Both of these rules were applied to only the junction section. The two optimization layouts are illustrated in Figure 4, with two symmetry axes (only a quarter of the part was modeled).

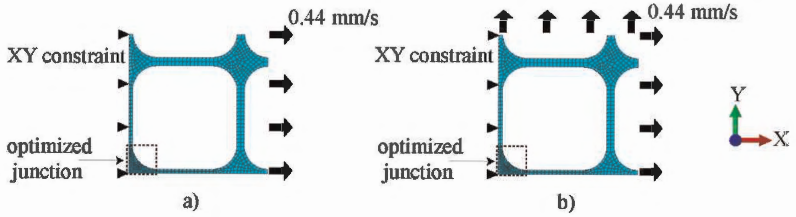

Figure 4. Topology optimization layout: a) uniaxial test; b) biaxial test. Only a quarter of the unit was modeled utilizing symmetry.

3.2 *Optimization results*

Results of the topology optimization are shown in Figure 5. The curved profile of the junction was nearly removed for both uniaxial and biaxial simulation tests. Results for the unixial test (Figure 5a) showed that a junction with a reduction of 55% of lateral thickness could still sustain the axial loading applied. The stress distribution in a biaxial scenario was more critical, allowing for a lateral thickness reduction of 36% (Figure 5b).

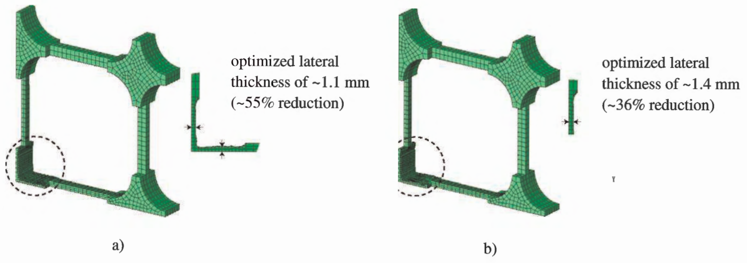

Figure 5. Topology optimization results: a) optimized section for uniaxial loading; b) optimized section for biaxial loading. Only a quarter of the unit was modeled utilizing symmetry.

3.3 *An alternative junction profile*

The theoretical results produced by topology optimization algorithms can provide insights on how to improve the geometry of geogrids. From the results described in Section 3.2, a new optimized junction profile was studied, matching the thickness of the ribs without the original curved profile (Figure 6b). Although the results in Section 3.2 allowed for a theoretical lateral thickness of the junction smaller than the ribs (Figure 5), continuity was maintained to avoid excessive distortion of the mesh. The same thickness of 5.8 mm was preserved from the initial profile, generating a volume reduction of 53%. The von Mises stress distribution for both initial and optimized junctions under uniaxial load are shown in Figure 6a. The load per unit width/strain comparison between initial and optimized profiles are shown in Figure 6c. A good agreement between the topology results and the actual stress distributions of the optimized junction was found. The stress distributions showed little variation between the two simulations, whereas the maximum load for the optimized model was 2% smaller than the initial model. This could be due to the lateral thickness reduction, since the initial model has a thicker rib-junction interface.

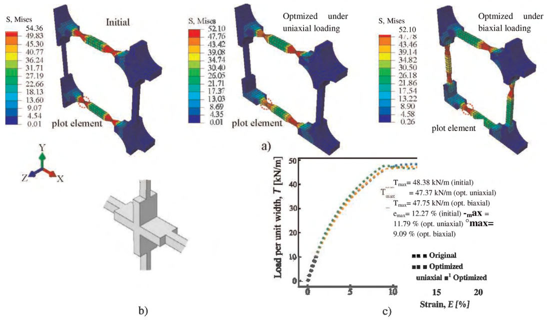

Figure 6. Comparison between initial and optimized junction profiles: a) von Mises stresses (true stresses) for maximum plasticity; b) 3D view of optimized junction; c) Load per unit width/strain curve for identified plot element (engineering stress/strain).

3.4 *Limitations and potential*

The optimization described herein considered the in-isolation response under uniaxial and biaxial tensile loadings. On the one hand, depending on the application, the loading can be more complex. On the other hand, in real applications, geogrids are confined in soil. Thus, the response of the composite material will be affected by factors related to the soil. Examples include: the particle size distribution and its relation to the geogrid openings; the relative movement of the geogrid and the soil. The soil-geosynthetic interaction is a function of the geogrid area, hence, changes in geometry will affect the mechanisms of load distribution within the junction and the reinforcement as a whole. The isotropic assumption affects the predicted resistance of the interface between ribs and junctions, that can also influence the optimization in this area.

Future models incorporating these aspects can utilize the non-destructive and easily-parametrized advantages of numerical simulations to propose more realistic optimized geometries for geogrids. As demonstrated, a general-purpose FE tool is an effective method to analyse geosynthetics, being able to generalize 3D stresses and strains from uniaxial tests.

4 CONCLUSIONS

In this study, numerical tensile tests of a geogrid were carried out, followed by a topology optimization to propose an alternative design of a junction element in a biaxial geogrid. First, a numerical model capable of simulating the tensile response of the in-isolation geogrid was developed using ABAQUS. The model featured a 3D geometry and an isotropic elasto-plastic constitutive model that was calibrated with experimental data from in-isolation tensile tests (MD). The results from the calibrated model allowed a deeper understanding on the stress distribution at the junction elements, where part of the profile was not contributing to the load bearing and local stability.

The TOSCA framework was then applied to optimize the topology of the junction profile, with a design domain set for material removal. The results obtained from the optimization design showed that the lateral thickness of the junction could be reduced in 55% (uniaxial loading) and 36% (biaxial loading), without compromising the initial stiffness and stability. The geometry produced by the optimization algorithm was used to propose an alternative junction profile with 53% less material that was also capable of resisting the same load conditions with a 3% resistance margin. These initial results are promising and can be extended to scenarios where a geogrid and the surrounding soil are modeled.

This study has demonstrated how a calibrated numerical model could be used to extend the physical element analysis through simulation (non-destructive) methods. The contribution of topology optimization in simplifying element shapes was also proved to be a suitable framework in finding new design solutions without compromising structural performance and integrity.

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