

Experimental and numerical investigation of granular materials for an increase of the collision safety of double-hull vessels

Christian Woitzik^{1,*}, Moshin Ali Chaudry², Peter Wriggers², and Alexander Düster¹

¹ Numerical Structural Analysis with Application in Ship Technology (M10), Hamburg University of Technology, 21073 Hamburg, Germany

² Institute of Continuum Mechanics, Leibniz University Hannover, 30167 Hannover, Germany

In the present contribution lightweight granulate like expanded glass will be considered as crash absorbing material in ship constructions. The granules were originally not intended for this application purpose, therefore the material behaviour for this load case has to be determined. To this end, the granulate is compressed in an aluminium cylinder to less than half of its initial height. Based on this experiment, the expanded glass is modelled as Mohr-Coulomb material within a nonlinear finite element simulation and the parameters of the constitutive equations are identified from the experimental data.

© 2016 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

1 Introduction

In modern shipbuilding double-hull designs are an established method to increase the stability and collision safety of a ship structure. To gain further improvements in collision safety either innovative types of ship hull structures have to be developed or filling of the void space between the hulls with crash absorbing and strength increasing material can be considered. The latter approach is suggested in [1] to be used with existing hull constructions to improve the penetration resistance in case of the collision with a bulbous bow using lightweight granular materials. As an example expanded glass as shown in Fig. 1 is considered. This material is usually applied for thermal isolation or as filling material for concrete or paint.

To determine the general material behaviour under compression an uniaxial compression test as shown in the next section is used.

2 Experimental set-up

The granular material is tested under uniaxial load in an aluminium cylinder with a diameter of 181 mm, a wall-thickness of 10 mm, and a height of 181 mm. The choice of a thin-walled cylinder allows small radial extension, so that the strain can be measured similar to the case of a soft oedometer in geomechanics [2]. The total load F_l and the transmitted load F_t as shown in Fig. 2 are measured. The difference between these two loads, $F_f = F_l - F_t$, is the force transmitted via the aluminium cylinder at the inner wall due to friction.



Fig. 1: Expanded glass material

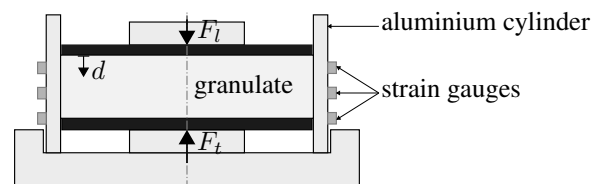


Fig. 2: Experimental set-up

3 Numerical model

The prescribed test is modelled with the commercial finite element package ABAQUS using a Mohr-Coulomb material law for the granulate and a linear elastic isotropic material model for the punch and die. The whole domain is discretized with eight-noded hexahedral elements applying a reduced integration. The chosen material models are valid up to approximately 5% strain [3]. The finite element simulation is based on an explicit time integration scheme. The Mohr-Coulomb model includes five material parameters, i.e. Young's modulus E_{gr} , Poisson's ratio ν_{gr} , friction angle Φ , dilatancy angle Ψ , and cohesion c . The following parameters were determined from triaxial compression tests in [1]: friction angle $\Phi = 21.5^\circ$, cohesion $c = 71500$ Pa, and dilatancy angle $\Psi = 1.023^\circ$. The parameters for the aluminium and steel parts of the model are $E_{st} = 206$ GPa, $E_{al} = 70$ GPa, and $\nu_{st} = \nu_{al} = 0.3$. The contact between the different materials, i.e. steel (punch, die), aluminium (cylinder), and granulate is considered with a penalty formulation including friction with the following coefficients $\mu_{st-al} = 0.19$, $\mu_{st-gr} = 0.5$, and μ_{al-gr} as unknown variable.

* Corresponding author: e-mail christian.woitzik@tuhh.de, phone +49 40 42878 6103, fax +49 40 42878 6090

4 Parameter identification process

Three parameters have to be identified from the experiments: Young's modulus E_{gr} , Poisson's ratio ν_{gr} and the friction coefficient μ_{al-gr} . To this end, we introduce the vector e_i which holds different data obtained from the experiments. In the same way we define the vector s_i , which contains the corresponding results of the finite element solution in dependency of the three unknown parameters. The residual vector $r_i = s_i - e_i$ describes the difference between the simulation results and measured data of the experiment. To find improved parameters, we perform a least squares fit based on the experimental data including – as different quantities – the loads F_l , F_f , and three strain values, $\varepsilon_1, \varepsilon_2, \varepsilon_3$, at different cylinder heights:

$$\min_{E, \nu, \mu} \left\| \{r_{F_l}, r_{F_f}, c \cdot r_{\varepsilon_1}, c \cdot r_{\varepsilon_2}, c \cdot r_{\varepsilon_3}\} \right\|^2 \quad (1)$$

In order to account for the different magnitudes of the data, the scaling factor c is introduced. Furthermore, constraints are defined for the parameters to obtain meaningful values. The least squares fit is carried out using MATLAB's `lsqnonlin` algorithm which is based on a trust-region-reflective algorithm [4]. To determine the quality of the estimated parameters, the correlation coefficients ρ_{ij} and the coefficient of determination R^2 are calculated following Krämer et al. [5].

5 Results and conclusion

Due to the underlying assumptions of the material model our simulation and therefore also the parameter identification is limited to a compression level of approximately 5%. The following parameters are used as initial guess: $E_{gr} = 4.4$ MPa, $\nu_{gr} = 0.1$, and $\mu_{al-gr} = 0.6$. As shown in Fig. 3a) a drop of two orders of magnitudes for the residual norm within the first seven iterations is obtained. From Fig. 3b) it is evident that the initial friction coefficient was a good choice, while Young's modulus is decreasing and Poisson's ratio is increasing. The following values are obtained: $E_{gr} = 2.9$ MPa, $\nu_{gr} = 0.3$, and $\mu_{al-gr} = 0.61$. From Fig. 4b) it can be observed that the frictional behaviour can not be modelled properly with the initial parameters, but the simulation results converge to the measured data for both data sets. As demonstrated in Fig. 4 the simulation is in good agreement with the experimental data up to approximately 10% compression.

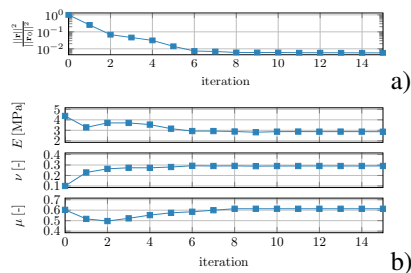


Fig. 3: Normalized residual norm and parameters over iteration process

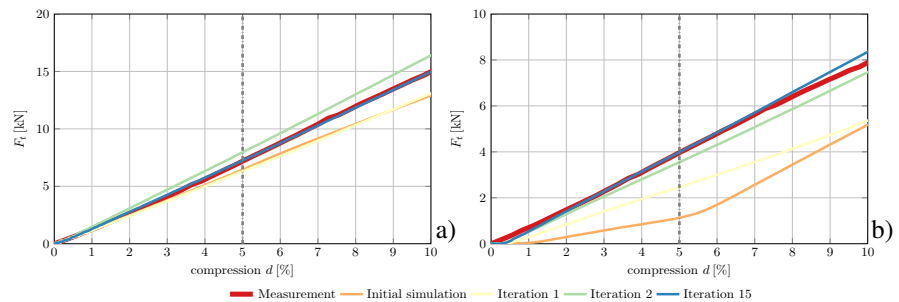


Fig. 4: a) Total force F_l over compression; b) frictional force F_f over compression

The following correlation coefficients are obtained: $\rho_{E, \nu} = -0.52$, $\rho_{E, \mu} = -0.37$, and $\rho_{\nu, \mu} = 0.71$. An increase of E will lead to a decrease of ν and μ , and an increase of ν leads to an increase of μ . The coefficient of determination is $R^2 = 0.99$ which indicates that the underlying model is suitable [5].

As a conclusion, the presented parameter estimation obtains reasonable results up to approximately 10% compression. For higher deformation states the material model can not cover the breakage of particles. This will be considered in future work by coupling particle methods with continuum models to improve the quality of our simulation so that we can study granules as crash absorbing material in ship constructions in more detail.

Acknowledgements The support of the DFG (Deutsche Forschungsgemeinschaft) under grant number DU 405/9-1 and WR 19/55-1 is gratefully acknowledged.

References

- [1] M. Schöttelndreyer. Füllstoffe in der Konstruktion ein Konzept zur Verstärkung von Schiffseitenhüllen. Techn. Univ. Hamburg-Harburg, Institut für Konstruktion und Festigkeit von Schiffen, PhD thesis Hamburg-Harburg, (2015).
- [2] D. Kolymbas and E. Bauer. Soft oedometer – a new testing device and its application for the calibration of hypoplastic constitutive laws. Geotechnical Testing Journal, **16**, No. 2, pp. 263-270 (1993).
- [3] Abaqus Analysis User's Manual, (2010).
- [4] T.F. Coleman and Y. Li. An Interior, Trust Region Approach for Nonlinear Minimization Subject to Bounds. SIAM Journal on Optimization, **6**, pp. 418-445 (1996).
- [5] S. Krämer, S. Rothe, and S. Hartmann. 2015. Homogeneous stress–strain states computed by 3D-stress algorithms of FE-codes: application to material parameter identification. Eng. with Comput. **31**, **1**, pp. 141-159 (2015).