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ORIGINAL RESEARCH PAPER

Modelling of closed-cell aluminum foam using Weaire–Phelan unit cells

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ABSTRACT

Design and testing of real materials is a costly process and usually requires some specific equipment. To alleviate this task numerical methods can be leveraged. In this work we show possible modelling technique for closed-cell material structure using Weaire–Phelan unit cells. As an example existing aluminum structures were used and modelled parametrically, allowing to establish different geometrical models for different applications. Numerical simulations for compression was also done on the developed models to reveal the material response. The influence on the cell wall thickness and the friction between the material and the compression plate was investigated. It was found that the friction coefficient has no significant effect on the material response, except in the case where bonded connection was assumed. It was also demonstrated that material response and the porosity controlled by cell wall thickness have an approximately linear relationship with each other. This method proved to be a flexible and alternative solution of real laboratory tests and targeted to reduce costs of material design.

KEYWORDS

closed-cell aluminum foam, finite element analysis, unit cell

1. INTRODUCTION

Foams are a kind of porous material which are produced artificially but resemble some existing structures in nature such as animal bones, honeycombs or even lungs. Among main features, these structures are lightweight with good impact absorbing properties [1,2]. Materials of this type have important combination of properties such as physical, thermal, mechanical and acoustical along with low densities [3].

Metal foams feature very high rates of volume to weigh even up to 0.98. Properties can be adjusted, thus new profiles can be derived out of the existing ones. There are different application areas which take benefit from these kinds of materials. The aerospace industry uses large aluminum and titanium foam panels for the tails of helicopters. Metal foams are also found in oil mist separators in different jet engines. In the medical industry, metal foams are used as implants for orthopedic or dental applications. Additionally, the structure of foam provides prerequisites for tissue growth into foam body. In civil engineering, metal foams can be used as electromagnetic and noise protective layer. In mechanical engineering, this type of material good for fast-moving parts, such as robot arms, tool manipulators, machine tables producing reduced weight and consequently reduced inertias with the same durability properties [4].

To obtain understanding of uniaxial behavior of metal foams tests in different axial directions were performed in [5]. Heat treatment influence on metallic foams is also discussed there. Such behaviors as collapse strength and elasticity modulus of different cell structures were studied in [6]. Density, wall thickness and cell size are among input parameters as influencers of mechanical response. Along with macro structures, micro level also has its impact on foams performance. Thus, morphological imperfections and their influence on

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performance of metallic foams were studied in [7]. Micro-scale deformation and macro-scale properties correlation was established for aluminum foams in [8]. Cell topology influence is studied as well, since mainly all mechanical structures expose nonlinear behavior. Load plateau effect was evaluated with regard to initial failure of structure in [9]. Understanding the damping characteristics of foams is important in various applications, such as in shock-absorbing materials, vibration isolation and acoustic insulation. The damping characteristics of foams can be characterized by its loss factor, which is the ratio of the energy dissipated to the energy stored during a vibration cycle. The loss factor depends on the foam's properties, such as its density, porosity and stiffness [10]. Researchers define two main groups of metallic foams, they are: closed-cell and open-cell structures. The main difference between them is that open-cell foams allow interconnection between cells and thus expose more softer and elastic behavior. Closed-cell structures on the contrary expose more rigid behavior [11]. Deformation mechanisms of closed-cell aluminum foams, different deformation modes were discussed and friction between cells as energy absorbing factor was evaluated in [12]. Investigation of wall behavior in a closed-cell foam under dynamic and static conditions was done in [13]. In this investigation, the internal parameters in the cell walls played a crucial role, like wavy imperfections that could decrease stiffness. Studies on the influence of lattice direction on compressive and shear stresses were conducted in [14]. Wall buckling phenomena and its influence on overall strength of structure were also introduced there.

Solid foams are produced by intrusion of some type of intermediate material into liquified metal, with even distribution of this inclusions. In recent years, these materials were exposed to growth in interest from researchers. Thus, commercial applications of metal foams were investigated, their production routes and methods studied with regard to costs and functional aspects, also future developments of the field are discussed in [15]. Various methods of production using various techniques and chemical materials were introduced in [16]. Tantalum, steel and titanium were among the other materials tested. The main techniques for creating foam were injection of gas, blowing of an agent, and the space holder technique. Such technologies of foam materials production were investigated as powder technology in [17]. Comparative analysis between foaming agents $CaCO_3$ and TiH_2 was held to predict the theoretical assumptions of each porous structure in [18]. Their costs were considered a significant factor in this work.

To obtain a geometrical model of metal foam there are different methods, among them computer tomography (CT) and Representative Volume Element (RVE) [19]. The microstructure of closed-cell aluminum foams was examined in a very detailed way from different manufacturers in [20]. Foams from such manufacturers as Alcan, Shinko Wire, Frauhofer and ERG have been observed under microscope optical photography. During the tests, the tensile results and compressive properties of the aluminum foams have been considered. There are two main models for closed-cell foams with regard to RVE technique. The idea to describe space partition into equal volume cells with least interface area led to creation of these two models. They are the Kelvin and the Weaire–Phelan models [21]. Kelvin and Weaire–Phelan unit-cell models were compared to each other in [22]. With the development of the finite element technique, attempts to try and predict properties of metal foams were discussed, based on different modelling techniques [23, 24].

Conduction of real mechanical tests on expensive or not yet produced materials is a time and money consuming process. With development of different numerical simulation-based tools it becomes logical to test materials in simulation environments before applying them in real environment. In our paper, in order to produce consistency of simulation tests for closed-cell aluminum foams, a scalable model is needed. A necessary structure is modeled by Weaire–Phelan method. Critical parameters are introduced as parameters and results of different simulations are compared to each other to find geometrical dependencies and trends. The influence on the cell wall thickness and the friction between the material and the compression plate were investigated. It was found that the friction coefficient has no significant effect on the material response, except in the case where bonded connection was assumed. It was also demonstrated that material response and the porosity controlled by cell wall thickness have an approximately linear relationship with each other. This method proved to be a flexible and alternative solution of real laboratory tests and targeted to reduce costs of material design.

2. MATERIALS AND METHODS

2.1. Introduction of material reference and its production technology

The applied material for modelling is called ALUHAB and was bought from Aluinvent Zrt. ALUHAB's matrix alloy is a composite material that can be foamed, and it is made up of small particles ranging from 80 nm to 20 μm in size. A compounding technology at high temperatures is used to produce the composite, ensuring that the particles that stabilize the foam are uniformly distributed throughout. The size of bubbles in this material is adjustable for different tasks. The minimal size corresponds to the size of the nozzle which distributes bubbles. For ALUHAB this size lies in range from 0.5 to 5.0 mm [25].

In Fig. 1, the block of the closed-cell foam can be seen and the specimen which was cut with CNC milling machine (CMX 600 V by DMG MORI) at the University of Debrecen [26]. According to specific parameters of the given material, the density of the specimen was approximately 600 kg m^{-3}.

Main dimensions of the specimen are 30 mm in diameter and 10 mm in height. The mass of the tested specimen is 2.2 g. Among the main parameters are porosity and density of material. In Table 1 the main parameters of the ALUHAB can be seen. The Young's modulus and the Poisson's ratio were determined in a previous research, see in [26].

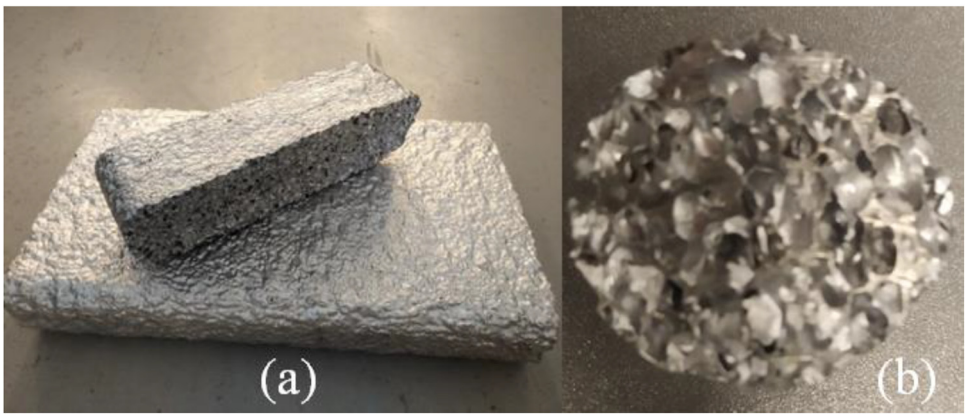

Fig. 1. ALUHAB brick produced by Aluinvent (a) and the specimen (b)

Table 1. The properties of the specimen

Property	Value
Mass [g]	2.2
Porosity [%]	89.27
Volume [mm^3]	796.33
Young's modulus [MPa]	2,374
Poisson's ratio	0.29

2.2. Modelling of the foam structure with Weaire–Phelan unit cell

In order to model and test the foam structure in numerical environment, the CAD model was introduced. The main idea of modelling lies in the usage of Weaire–Phelan cell structure, which is appropriate to model least interface area between cells in real closed-cell structures.

Two main units concluding the entire structure were modeled as CAD parts (Fig. 2). They are dodecahedron and tetrakaidecahedron according to Weaire–Phelan method.

In order to obtain scalable structures for different numerical tests with no need to rebuild constituting parts, a parametrization table was constructed to adjust wall thickness and unit size dynamically. A scaled model of Weaire–Phelan structure is shown in Fig. 3. This model was then used to construct different geometries with different parameters.

In order to produce shallow structure with adjusted porosity of material parametrically, constituting units were cut and wall thickness introduced as parameter in parameters table, along with unit size scale parameter (Fig. 4).

Given these building bricks, different geometries with adjusted parameters were generated for the numerical tests.

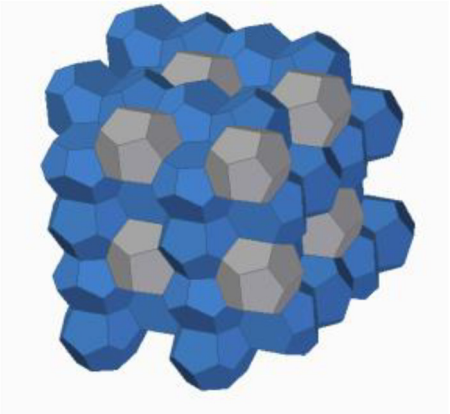

Fig. 3. Scaled Weaire–Phelan structure

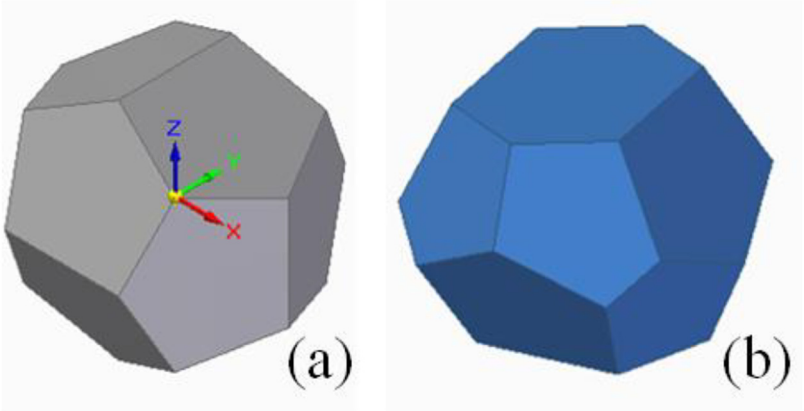

Fig. 2. Dodecahedron (a) and Tetrakaidecahedron (b)

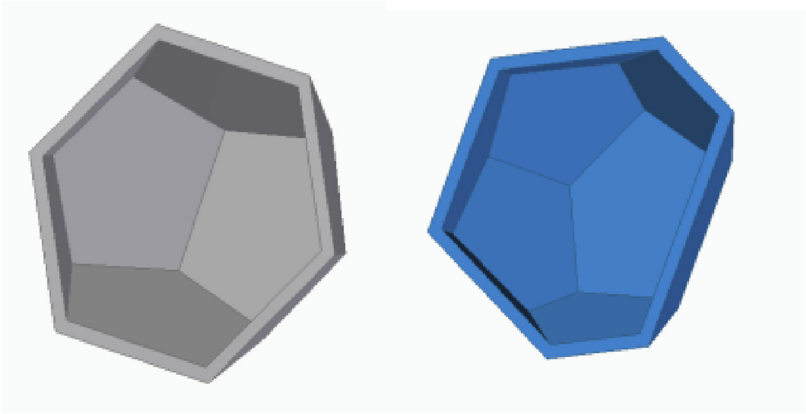

Fig. 4. Internal structure of constituting units

2.3. Geometry generation

For the geometry tests, the porosity of structure and its influence on mechanical behavior were of particular interest. In order to adjust porosity of the specimen, wall thickness parameter was introduced in modelling section, which was leveraged to generate five corresponding geometries. In Fig. 5 two corner cases are represented.

Dependency between wall thickness of structure and porosity was calculated based on

$$P\ (\%) = \frac{V_T - V_S}{V_T} \times 100, \tag{1}$$

where V_T represents total volume of structure, V_S represents volume of solid part of structure and P is porosity in percent.

For this type of geometry, volume of solid component calculation is not a trivial task; CAD software was used to retrieve this data for different geometries. Dependency between wall thickness and porosity of structure are presented in Table 2.

The porosity of structure can be also modified by adjustment of unit size without the change of wall thickness. In order to analyze the behavior of different unit sizes, five different geometries were generated. In Fig. 6 two corner cases are represented. From the figure it can be seen that with comparison to the modification of wall thickness, cell size change does not have much influence on the bulkiness and consequently on the porosity of the structure.

Table 2. Dependency of wall thickness and porosity

	Wall thickness [mm]	Porosity [%]
S1	0.1	88.72
S2	0.2	78.22
S3	0.3	68.61
S4	0.4	59.86
S5	0.5	51.94

2.4. Finite element model

Finite element analysis was conducted using ANSYS Mechanical solver. For all geometries the same boundary conditions and loads were established. For better results specimens were fixed between two rigid plates, see in Fig. 7. Material for the specimen was assigned based on properties from the real product.

Since this type of material is usually supposed to perform under compressing loads, displacement of 0.2% in direction of compression was introduced to the upper plate. The second plate was assigned as a fixed support. In order too measure mechanical response of the structure, unidirectional force response was measured with the numerical simulation. In order to produce reliable results from numerical tests, mesh convergence analysis was conducted on the generated geometry. The results of the mesh convergence analysis can be seen in Fig. 8. Error values were calculated relative to the finest mesh results.

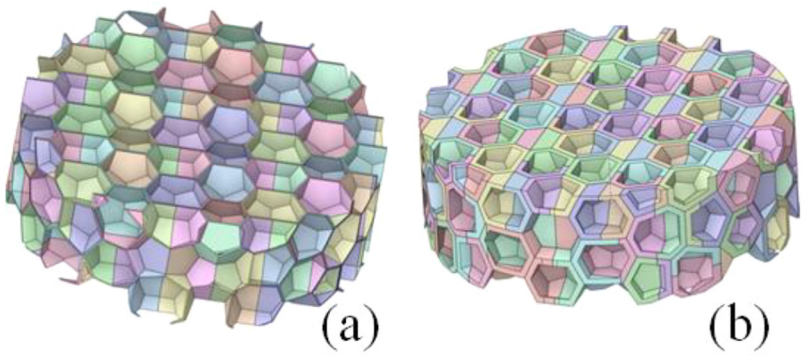

Fig. 5. Geometries for different porosity by wall thickness, $P = 88.72\%$ (a), $P = 51.94\%$ (b)

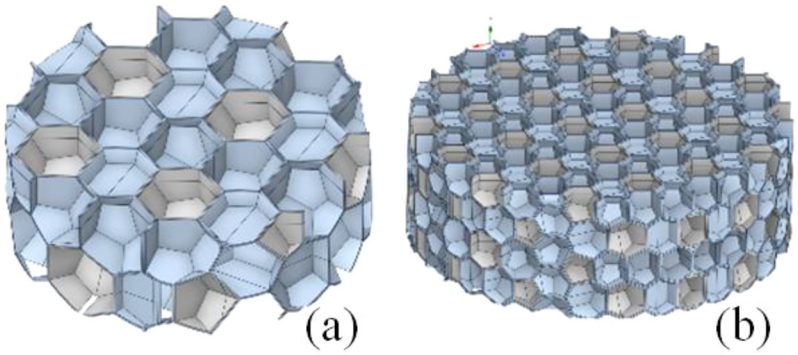

Fig. 6. Geometries for porosity by unit size, $P = 90.71\%$ (a), $P = 81.09\%$ (b)

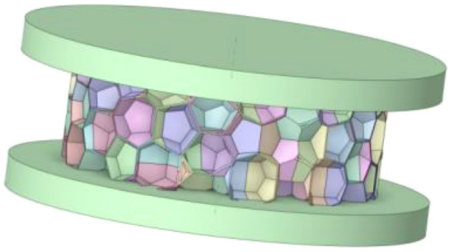

Fig. 7. Specimen setup

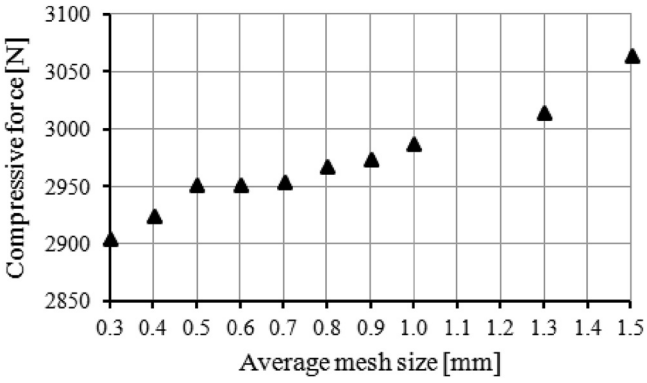

Fig. 8. Results of the mesh convergence analysis

It is supposed that results are plausible if an error does not exceed 5%.

Time to complete numerical simulation was also taken in consideration when choosing best mesh sizing for all numerical tests. Relative errors for different mesh sizes are collected in Table 3.

Based on aforementioned considerations mesh size with value 1 mm was chosen as compromise between relative error and computation time.

3. RESULTS AND DISCUSSION

Different numerical simulations with different geometries and friction coefficients between specimen and steel plates were conducted for the influence of wall thickness. This data was collected in Table 4, where each cell represents force response in Newtons [N].

Table 3. Mesh size – relative error

Mesh size [mm]	Relative error [%]
1.5	5.403
1.3	3.828
1	2.779
0.9	2.462
0.8	2.208
0.7	1.895
0.6	1.771
0.5	1.685
0.4	0.767
0.3	0.000

According to this data, the graphs were generated to represent the influence of friction coefficient between plates and the specimen on force reaction. Each curve represents single geometry with specific porosity. It is clearly seen that friction coefficient does not provide significant influence, until the switch between moving and bonded allowance happens (Fig. 9).

Porosity influence analysis shows that structure response is almost linear to changes in wall thickness (Fig. 10) and its dependency is approximated by (2) as

$$F_R(bonded) = 0.7459\times P^2 - 170.88\times P + 9822.8,$$
$$F_R(frictionless) = 0.2594\times P^2 - 67.78\times P + 4315.1 \quad (2)$$

Unit size response is shown in Fig. 10 and approximated by (3) as

$$F_R = -0.4267\times P^2 + 13.74\times P + 2671.5. \quad (3)$$

Data for approximate points is collected in Table 5. It shows that gains from the change of unit size are smaller than gains from wall thickness size, given the same porosity and, consequently, the same material mass, see in Fig. 11.

Table 4. Force reaction for different porosities and friction coefficients generated by wall thickness

Specimen	P [%]	Frictionless	$\mu = 0.25$	$\mu = 0.5$	$\mu = 0.75$	Bonded
S1	88.72	325.9	326.6	326.8	327	517.6
S2	78.22	628.5	629.2	629.8	630.3	1,050.2
S3	68.61	922.8	923.6	924.6	925.6	1,624.9
S4	59.86	1,099.5	1,101.8	1,104	1,106	2,208.2
S5	51.94	1,535.2	1,541.4	1,545.9	1,550.2	2,988.5

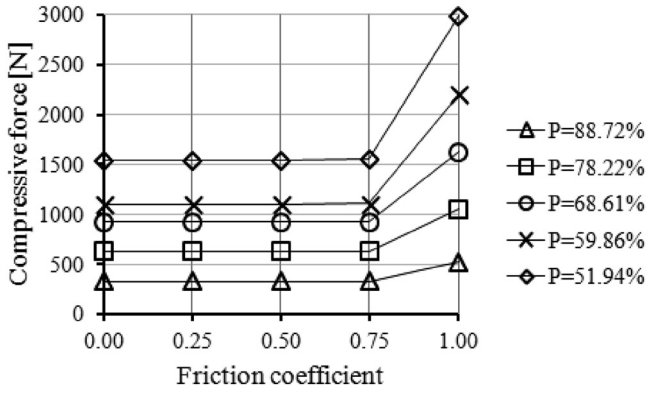

Fig. 9. Friction coefficient – structure response dependency for different porosities

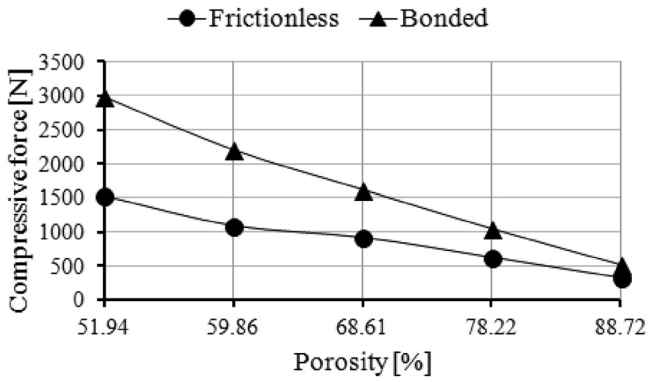

Fig. 10. Wall thickness – structure response dependency for bonded and frictionless contact

Table 5. Force reaction for different porosities generated by unit size

Specimen	V_{TDH} [mm^3]	V_{DDH} [mm^3]	P [%]	F_R [N]
S6	3.51	3.54	81.09	977.6
S7	4.72	4.75	83.92	834
S8	6.66	6.7	86.36	648.5
S9	10.039	10.104	88.65	559.4
S10	16.74	16.85	90.71	400

V_{TDH} represents the volume of tetrakaidecahedron and V_{DDH} represents the volume of dodecahedron for each unit size.

In a previous article [26], closed-cell aluminum foam was modeled in a similar way for a special geometric design, and the compression test of the real aluminum foam was also carried out. In the case of the present investigations, it can be stated that the results of the numerical tests are closely approximate to the previous laboratory measurement [26].

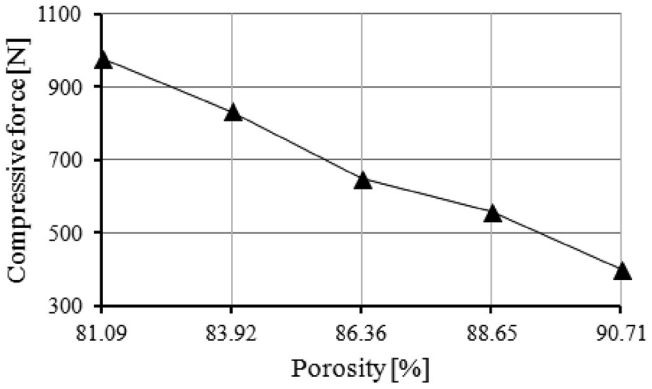

Fig. 11. Cell size – structure response dependency

4. CONCLUSION

This paper discusses the modelling possibilities of closed-cell metal foam structures with Weaire–Phelan unit cells. Existing aluminum foam was referenced as a modelling example and then implemented in CAD environment. CAD model was prepared in parametric way, which allowed to adjust the geometry for different cases, without changing the structure of the material. By using this method, different geometric models were generated and tested in the numerical simulations. The influence of porosity on mechanical response of the structure, geometric models were prepared in such way that allows to reveal trends, which were presented. The influence on the cell wall thickness and the friction between the material and the compression plate were investigated. It was found that the friction coefficient has no significant effect on the material response, except in the case where bonded connection was assumed. It was also demonstrated that material response and the porosity controlled by cell wall thickness have an approximately linear relationship with each other. This method allows to test different geometric parameters and their influence on structure behavior, which can reduce design costs of the real materials.

Conflict of interest: The 4th author, Tamás Mankovits is a member of the Editorial Board of the journal. Therefore, the submission was handled by a different member of the editorial team.

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