[7] *Palmyra 2.3*, MatSim GmbH, Zürich, Switzerland, http://www.matsim.ch.
[8] L. D. Landau, E. M. Lifshitz, *Theory of Elasticity*, Vol. 7, 3rd ed., Oxford Butterworth-Heinemann, Woburn, MA **1999**.
[9] O. C. Zienkiewicz, R. L. Taylor, *The Finite Element Method, Vol. 1: The Basis*, 5th ed., Butterworth-Heinemann, Oxford, U.K. **2000**.
[10] a) E. H. Kerner, *Proc. Phys. Soc.* **1956**, *69*, 808. b) C. van der Pol, *Rheol. Acta.* **1958**, *1*, 198. c) J. C. Smith, *J. Res. Natl. Bur. Stand.* **1974**, 355, *78A*, 355. d) J. C. Smith, *J. Res. Natl. Bur. Stand.* **1975**, *79A*, 419. e) R. M. Christensen, K. H. Lo, *J. Mech. Phys. Solids* **1979**, *27*, 31.
[11] Z. Hashin, *J. Appl. Mech.* **1962**, *29*, 143.
[12] Because of the 10 to 1 diameter ratio assumed for big and small spheres, the computer models studied in this work were comprised of $10^3 f_s/f_b$ small spheres per each big spheres.
[13] We have found, by using image analysis, that the random hard-fiber Percus–Yevick statistic is representative for "real" industrial fiber reinforced composites.[5,14]
[14] A. A. Gusev, P. J. Hine, I. M. Ward, *Comp. Sci. Techn.* **2000**, *60*, 535.
[15] P. J. Hine, H. R. Lusti, A. A. Gusev, *Comp. Sci. Techn.* **2002**, *62*, 1445.
[16] H. R. Lusti, P. J. Hine, A. A. Gusev, *Comp. Sci. Techn.* **2002**, *62*, 1927.
[17] A. A. Gusev, J. J. M. Slot, *Adv. Eng. Mater.* **2001**, *3*, 427.
[18] A. A. Gusev, H. R. Lusti, *Adv. Mater.* **2001**, *13*, 1641.

Fracture Resistant Structures Based on Topological Interlocking with Non-planar Contacts**

By *Arcady V. Dyskin*,* *Yuri Estrin*, *Elena Pasternak*, *Han C. Khor*, and *Alexei J. Kanel-Belov*

Topological interlocking based on matching of non-planar surfaces of contacting elements forming a structure is considered. A generic block shape permitting masonry-type arrangements of blocks is discussed. The results of indentation tests on a plate-like assembly of such blocks are presented. The main feature interesting for applications is the localized character of fracturing that does not spread from a failed element into the rest of the structure. The possibility of producing continuous layers tolerant to failures of individual elements, combined with a high bending flexibility of such structures, gives promise for a range of applications, in particular in protective coatings.

In a foregoing communication to this Journal[1] we have considered a principle of topological interlocking of identical convex elements of a particular shape that leads to layer-like structures with special properties. The main feature of such assemblies is that each element is locked within the structure by purely geometrical (kinematical) constraints, provided that the assembly itself is constrained at the periphery. Thus, there is no need in affixing the elements to each other in any conventional way. Moreover, it was suggested that the absence of physical connection between the elements should

[*] *Prof. Y. Estrin*
Institut für Werkstoffkunde und Werkstofftechnik
Technische Universität Clausthal
D-38678 Clausthal-Zellerfeld (Germany)
E-mail: Juri.estrin@tu-clausthal.de
Prof. A. V. Dyskin, Dr. E. Pasternak, H. C. Khor,
Dr. A. J. Kanel-Belov
Department of Civil and Resource Engineering
The University of Western Australia
35 Stirling Highway, Crawley WA 6009 (Australia)

[**] *Funding by the Australian Research Council through the Discovery Grant, Grant DP0 210 574 (2002-2004) is acknowledged. One of the authors (K-B) acknowledges support from the University of Western Australia through a Gledden Senior Visiting Fellowship. The authors are grateful to B. H. G. Brady, M. Fahey, A. Deeks, A. N. Galybin and M. F. Randolph for useful and stimulating discussions. The authors also acknowledge the help of A. Alla, P. Howell, and O. Nelson in manufacturing the blocks and setting up and conducting the tests.*

  1438-1656/03/0303-0116 $ 17.50+.50/0

lead to enhanced fracture toughness as cracks cannot spread from one element to another.

Starting with the regular tetrahedron as the basic element, some other element shapes were considered[1] which are essentially "derivatives" of the basic one as far as interlocking is concerned. In all these cases, interlocking was achieved with simple convex polyhedra. An obvious benefit of the convex shapes is the absence of stress concentrators as opposed to conventional interlocking bricks joined together by special connectors, as sometimes done in building industry.[2,3] The downside of the topological interlocking considered by Dyskin and co-workers[1] is a reduced contact area of the elements, which leads to a loss of the load bearing capacity of the assemblies. However, the benefits of the topological interlocking and full contact between the elements can be combined, provided that interlocking is achieved by non-planar surfaces sufficiently smooth to minimize stress concentrations. In the present communication we consider such geometrical shapes and discuss the properties of structures built on this principle.

We consider topological interlocking by appropriately chosen matching *curved* surfaces of the contacting elements. An example of such interlocking is shown in Figure 1 where the convex parts of the surface of one element match the concave parts of the other and vice versa. If the two surfaces are brought in contact, no relative movements in the xy-plane are possible under a constraint in z-direction.

In a sense, this kind of interlocking can be viewed as a large-scale version of friction caused by the interaction of asperities on two rough surfaces in contact. However, the matching surfaces provide full contact as opposed to local and irregular nature of interacting asperities prone to failures. Of course, conventional friction between the contacting curved surfaces is also present in any type of topological interlocking, but it is a secondary effect as compared to the resistance to the element displacements provided by the geometrical constraints.

It should also be noted that under load the concave parts of the surfaces might produce stress concentrations. However, owing to the relative smoothness of the surface these stress concentrations will be mild as compared with the ones produced by connectors in conventional interlocking bricks.

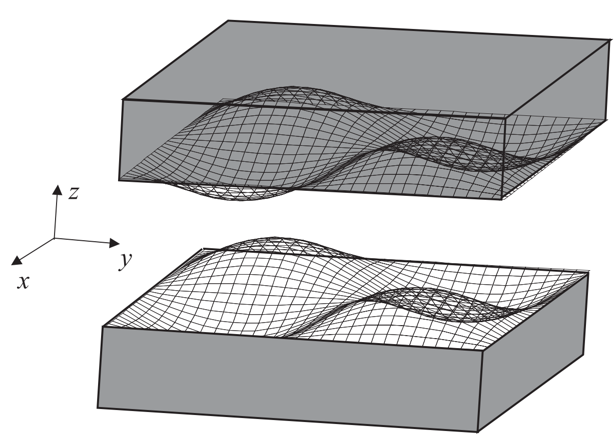

Fig. 1. A sketch of a pair of blocks with matching concavo-convex surfaces. The upper block is shown semi-transparent to display the hidden concave parts of its surface which is a replica of the corresponding surface of the lower block.

The above idea of exploiting the interplay between the matching concavity and convexity of the contacting surfaces can be used to generate a special class of interlocking building blocks with considerable potential for development of novel materials and structures. In order to ensure versatility of the building blocks, the matching surfaces are to be designed in such a way that they can be assembled to both planar and corner masonry-type structures. Therefore, the surfaces shown in Figure 1 should be modified to permit matching and interlocking when one block is shifted by half-length with respect to the other or, for corner structures discussed in the next section, shifted and rotated by 90°.

These conditions can be satisfied with a block shape shown in Figure 2 where two opposite non-planar surfaces are described by the following equations:

$$z_1(x,y) = \Delta h\varphi(x)\varphi(y) + h;$$
$$z_2(x,y) = \Delta h\varphi(x+a)\varphi(y) - h \quad (1)$$

Here, $\varphi(x)$ is an arbitrary function satisfying the conditions of symmetry and periodicity as well as the boundary conditions

$$\varphi(x) = \varphi(-x);$$
$$\varphi(x) = \varphi(x+2a);$$
$$\varphi(0) = 1;$$
$$\varphi(a) = -1;$$
$$\varphi'(0) = \varphi'(a) = 0 \quad (2)$$

With reference to the bone-like shape of this block we call it *osteomorphic*. The degree of curvature of the surfaces is controlled by the parameter $\Delta h < h$. The length scale of the block "a" is arbitrary; the ratio of 2 chosen for the sizes in the x- and y-directions is necessary for corner structures (Fig. 3a). The block shape in Figures 2 and 3 was obtained by choosing

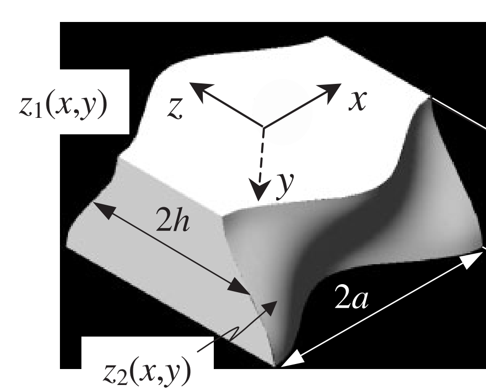

Fig. 2. Building block with two opposite non-planar surfaces permitting masonry-type assemblies (osteomorphic block).

$h = 3a/4$ and using a fourth order polynomial, $\varphi(x) = 2a^{-4}(x^2 - a^2)^2 - 1$, on the interval $(-a, a)$, continued beyond this interval to form a periodic function with period $2a$.

Figure 3 shows examples of corner and plate-like structures assembled from osteomorphic blocks. Half-blocks need to be used to finish the edges of the structures. A similar block based on a cosine form of function φ was proposed earlier for use in building industry.[4]

To study the mechanical properties of a plate assembled from osteomorphic blocks vis-à-vis a solid plate of the same dimensions and from the same material we performed concentrated loading tests similar to those described by Dyskin and co-workers.[1,5] Both the blocks and the solid plate were cast from polyester casting resin Polylite 61-209. The resin is translucent, so that internal fractures formed during the test could easily be seen. It is brittle with a fracture toughness of about 0.6 MPa m$^{1/2}$. It has a high compressive strength of about 140 MPa and a low Young's modulus of 4 GPa,[6] which makes deformations easily measurable. The assembly consisted of 14 × 7 osteomorphic blocks of the shape described above and with the dimensions $a = 19$ mm, $h = 14.25$ mm, and $\Delta h = 4.75$ mm completed with rows of half blocks at the edges. The assembly and the reference solid plate were held in a specially designed frame with controlled lateral load (Fig. 4). The concentrated loading tests were performed on an Instron loading machine with a constant rate of indentor displacement of 2 mm/min.

Some load vs. indentor displacement curves are shown in Figure 5 for two levels of lateral pressure. While the effect of lateral pressure on the solid plate is negligible, the deformation behavior of the assembly is strongly pressure dependent. The assembly has a much lower bending stiffness than the reference plate as manifested in the difference in the slope of the curves. This feature was already discussed for assemblies of interlocked tetrahedra.[5,7] The assembly also has a markedly lower bearing capacity, the reference plate failing at the load of about 9.5 kN. On the other hand, the assembly can sustain considerable deflections comparable with its thickness. This, together with high bending flexibility, can be beneficial for applications where large deformations are required. It should also be noted that the assembled structure exhibits a significant irreversible deflection (about 4 mm for the unloading curve shown in Fig. 5) suggesting a degree of "formability".

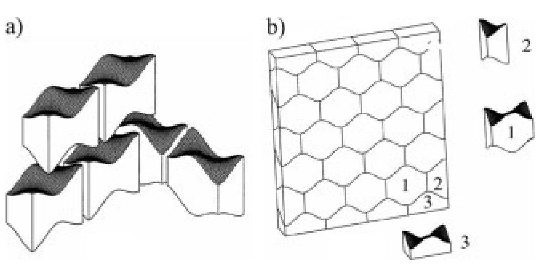

Fig. 3. Assembling of masonry structures: a) Principle of assembly of layer and corner structures. b) Layer of osteomorphic blocks (1) completed with half-blocks (2) and (3).

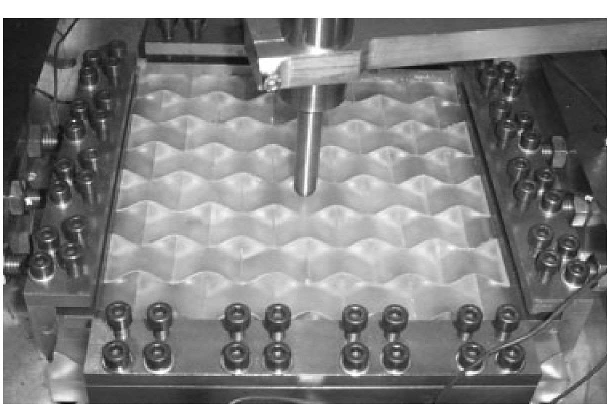

Fig. 4. Experimental set-up for the indentation test.

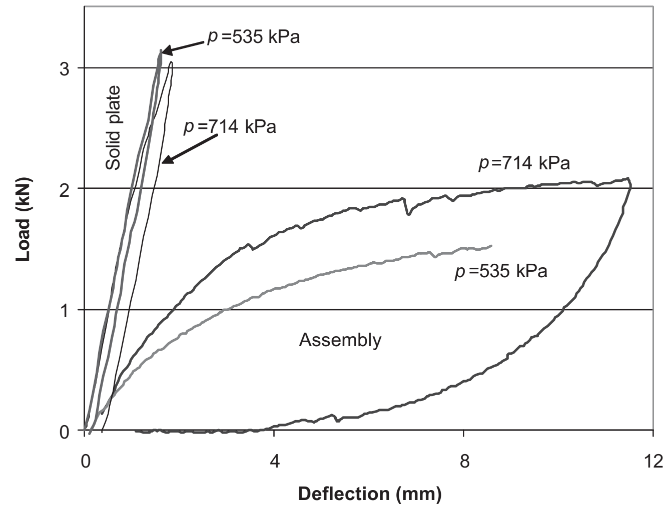

Fig. 5. Loading vs. deflection curves for the assembly and the solid plate for two values of lateral pressure, p = 535 kPa and p = 714 kPa. Both the loading and the unloading branches are shown, apart from the case of assembly at p = 535 kPa.

The most interesting property which makes this type of structures particularly attractive for potential applications is the localized character of failure. Drastically different failure patterns in the solid plate and the assembly are shown in Figure 6. While in the first case fracturing involved the whole plate (cracks initiated in the middle traversing the entire plate), in the second case only a small group of elements failed, the rest of the assembly having maintained its structural integrity.

The localized character of failure in the assembly owes to the fact that the blocks are not joined together so that cracks are not able to propagate across an interface. Furthermore, the geometry of the blocks and their masonry-type arrangement permit the assembly to keep its integrity even if some blocks are missing. It is sufficient for an individual block within the structure to be supported by only two neighbors at the sides with curved surfaces. If the osteomorphic blocks were replaced with conventional rectangular bricks held together by friction only, the property of localized failure would be retained. However, the small scale and the irregular character of asperities responsible for the friction would produce a considerably lower load bearing capacity. Indeed, to

a)
b)

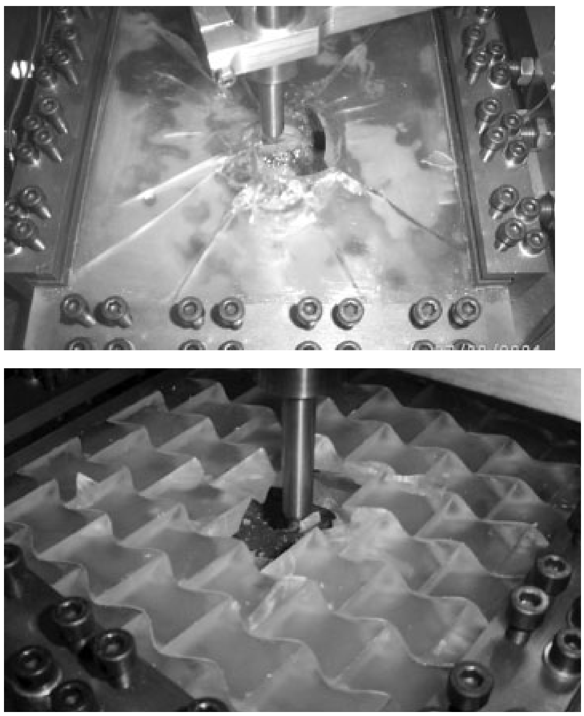

Fig. 6. Failure patterns: a) The reference solid plate, b) the assembly loaded at a joint between two blocks.

sustain the indentation load of, say, 1.5 kN observed in the above tests under the lateral pressure of about 500 kPa (Fig. 5) on an equivalent rectangular block with lateral area of 24 cm^2 would require an unrealistically large friction coefficient in excess of 1.25.

Topological interlocking of elements based on matching of curved contacting surfaces offers flexible structures highly tolerant to local failures. The main distinction of these structures from those based on interlocked polyhedra is in their ability to form continuous layers which can be used for surface protection, such as claddings or linings. Such structures are especially promising in the case of brittle materials (ceramics, intermetallic compounds, etc.), as failure of individual blocks does not lead to global failure, in contrast to solid structures. The principle of topological interlocking is obviously scale-independent, which offers a possibility of going down to micro or nanostructured layers once a suitable manufacturing technology is found. Another interesting avenue is design of composites in which elements of the same geometry, but made from different, even totally dissimilar, materials, are combined in a desired proportion.

Received: July 29, 2002

[1] A. V. Dyskin, Y. Estrin, A. J. Kanel-Belov, E. Pasternak, *Adv. Eng. Mater.* **2001**, *3*, 885.
[2] K. B. Anand, K. Ramamurthy, *J. Architect. Engng.* **2000**, *6*, 45.
[3] F. Vasco Costa, in *Proc. 23rd Int. Conf. on Coastal Engineering*, Oct. 4–9, 1992, Venice, Amer. Soc. Civil Eng. **1993**, 1091.
[4] D. A. Robson, *Patent DE-AS 2 554 516*, **1978**.
[5] A. V. Dyskin, Y. Estrin, A. J. Kanel-Belov, E. Pasternak, *Scripta Mater.* **2001**, *44*, 2689.
[6] A. V. Dyskin, R. J. Jewell, H. Joer, E. Sahouryeh, K. B. Ustinov, *Int. J. Fract.* **1994**, *65*, R77.
[7] Y. Estrin, A. V. Dyskin, A. J. Kanel-Belov, E. Pasternak, in *IUTAM Symp. on Analytical and Computational Fracture Mechanics of Non-homogeneous Materials* (Ed: B. Karihaloo), Kluwer, Norwell **2002**, p. 51.

Mechanical Properties of a High-Strength $Al_{90}Mn_8Ce_2$ Alloy**

By *J. C. Li*,* *Z. K. Zhao*, and *Q. Jiang*

Considerable efforts have been devoted to the development of novel, lightweight engineering materials during the last decades. Aluminum alloys have received considerable attention especially in the automobile and aerospace industries because of their high specific strengths. To further increase the strength of conventional crystalline aluminum alloys with good ductility, rapid solidification methods (RS), and mechanical alloying methods (MA) have been utilized successfully to decrease grain size, to increase solid solubility, and to obtain an amorphous matrix.[1–4] Among Al alloys, amorphous, melt-spun ribbons of Al–Ln–Tm (Ln = rare earth, Tm = V, Cr, Mn, Fe, Mo) alloys possess high strength.[4–9] The tensile strength of these alloys is greater than 1000 MPa, the highest strength being 1250 MPa. If α-Al nanoparticles or icosahedral quasi-crystals are embedded in an amorphous matrix with coherent interfaces, the strength of the alloy is further improved.[2–5,10–13]

Although these ribbons exhibited ultimate strengths exceeding the performance of conventionally produced Al alloys by a factor two to three, they cannot be directly utilized as structural materials due to their small size. Thus, powder metallurgy (P/M) was recently used to fabricate bulk samples.[14–15] In this contribution, the mechanical properties, such as strength, plasticity, and wear resistance, of a

[*] *Prof. J. C. Li, Prof. Z. K. Zhao, Prof. Q. Jiang*
The Key Laboratory of Automobile Materials
Ministry of Education and Department of Materials Science and Engineering
Jilin University
Changchun 130025 (China)
E-mail: jiangq@jlu.edu.cn

[**] *The authors gratefully acknowledge the financial support of NNSFC under Grant (50025101) and by the Department of Science and Technology of the Jilin province of China (19980542).*

  1438-1656/03/0303-0119 $ 17.50+.50/0