Solid Mechanics and Its Applications

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MATERIALS WITH NOVEL ARCHITECTONICS: ASSEMBLIES OF INTERLOCKED ELEMENTS

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1. Introduction

In a recent communication [1] we proposed a new material architecture that is based on regular assemblies of identical interlocked elements. The topology of packing of the elements prevents each individual 'building block' from breaking out by its immediate neighbours. We believe that the theoretical possibility of such interlocked structures opens up a new direction for creating strong and flexible composite materials with high impact resistance. While the interlocked elements form a skeleton structure that can provide structural integrity of the composite, a second phase can be selected to satisfy specified functional requirements, e.g. with regard to electrical or thermal conductivity, sound attenuation, etc. Since the properties of the assemblies are determined by their topology, rather than by the size of the 'building blocks', the topologically motivated materials design principle proposed can be used in large scale structures, as well. In the present paper, we investigate some mechanical properties of materials whose design is based on the topological interlocking principle.

In principle, the strength of a composite can be increased if the elements of the skeleton assembly are directly connected to one another. In the mechanical sense, a second phase ('binder') would then play the role of a 'buffer' that inhibits the transfer of dislocations or cracks from one particle to another. Interlocking can, of course, be achieved by equipping the building blocks with special connectors, as often done in the building industry with self-locking bricks. Obviously, the connectors are stress concentrators that impose severe limitations on the overall strength of the structure. We took a different approach to designing interlocked structures. It is based on the use of the topological possibility of establishing self-locking in assemblies of simple convex shaped elements free of stress concentrators. A particular realisation of this idea is an interlocked layer structure consisting of identical *tetrahedron-shaped* elements packed in a special way. Some interesting findings of the first mechanical tests done on an experimental specimen with the proposed architecture are presented below. Furthermore, possible mechanisms of failure of interlocking assemblies are considered.

2. Self-locking assembly of tetrahedrons

The proposed material architecture is based on the fact [1] that there exist three-dimensional shapes of identical blocks that can form regular interlocked assemblies. In essence, the interlocking shapes are such that while some parts of the shape prohibit displacements of a block in one direction, other parts prevent it from moving in the opposite direction, Figure 1. When placed in a confinement at its periphery, an assembly of this kind will preserve its structural integrity without any adhesive or connectors.

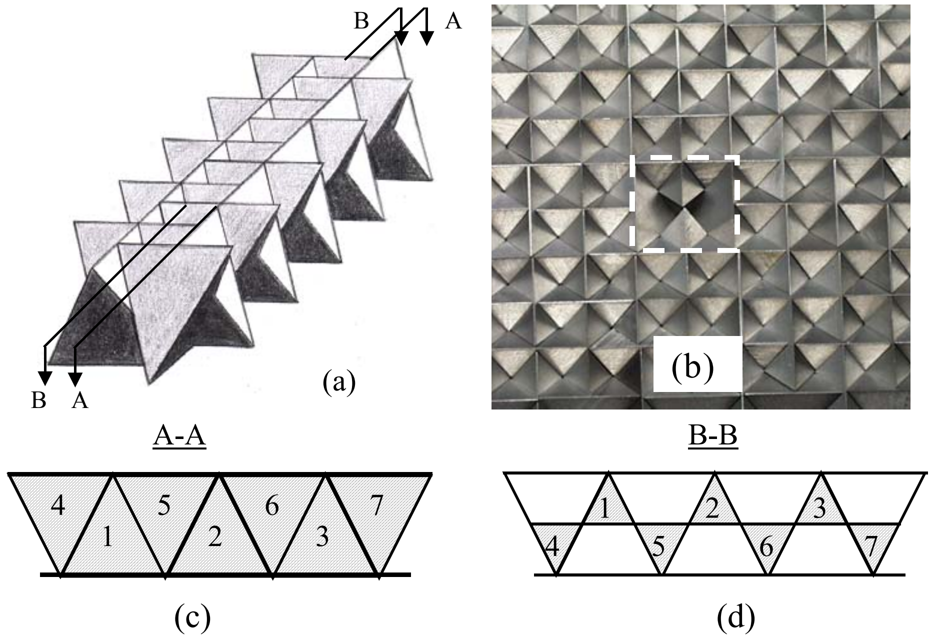

Figure 1. Assembly of interlocked tetrahedrons: general (a) and top (b) views and two parallel cross-sections (c, d). In the top view (b) one tetrahedron is missing. This is indicated by white broken lines. In the central cross-section, A-A (c), any one of the numbered elements can be removed by downward or upward movement. In the other cross-section, B-B (d), each element is locked by elements of the adjacent row of tetrahedrons. Note that the elements with the same number in (c) and (d) belong to the same tetrahedron.

The first system we considered, *viz.* a self-locking assembly of identical tetrahedrons, is shown in Figure 1. A fragment of the whole assembly is sketched in Figures 1a, b. Figures 1c and 1d show two parallel cross-sections. While in the central cross-section A-A (Figure 1c) blocks numbered 1-3 are prevented from moving upwards, in an offset cross-section, B-B (Figure 1d) they are prevented from downward movement by elements located in the adjacent row of tetrahedrons. The recipe for constructing such an assembly is evident from Figure 1a: one edge of each tetrahedron lies in one of the two parallel planes delimitating the layer, while the opposite edge lies in the other. Two neighbouring tetrahedrons are attached to each other in such a way that a vertex on the 'upper' edge of one of them contacts the middle of the 'upper' edge of the other. Conversely, the middle of the 'lower' edge of the first tetrahedron is in contact with a vertex on the 'lower' edge of the second one. The 'upper' edges of the two are normal to each other. The same holds for the 'lower' edges. Each tetrahedron has four neighbours. The arrangement obtained imposes kinematic constraints that provide self-locking of the structure. Two of the four neighbours of each individual tetrahedron preclude its removal by upward movement, while two others lock it against removal in the opposite direction.

Additional external constraints have to be imposed to stabilise the structure against lateral movement of the elements. In the tests described below this was achieved by placing it in a special rigid frame, Figure 2.

3. Deformation under concentrated load

To implement the above materials design concept in a real specimen, an assembly of 100 interlocked tetrahedrons was produced [1]. The tetrahedrons with the edge length of a = 1 cm made from a common use Al-Mg-Si alloy were used in the as-machined condition. The assembly was placed in a rigid steel frame, Figure 2a and tested in an Instron machine under concentrated load. The displacement of the indentor (i.e. that of the cross-head of the machine) and the applied force were recorded. In addition, the cental deflection, i.e. the displacement of the edge of the central tetrahedron at the bottom side of the layer, was measured. The loading was stopped when the tetrahedrons adjacent to the indentor had rotated towards it to the extent that they actually touched the indentor. The diameter of the indentor (1 cm) was chosen to exactly match the size of the 'unit cell' of the assembly.

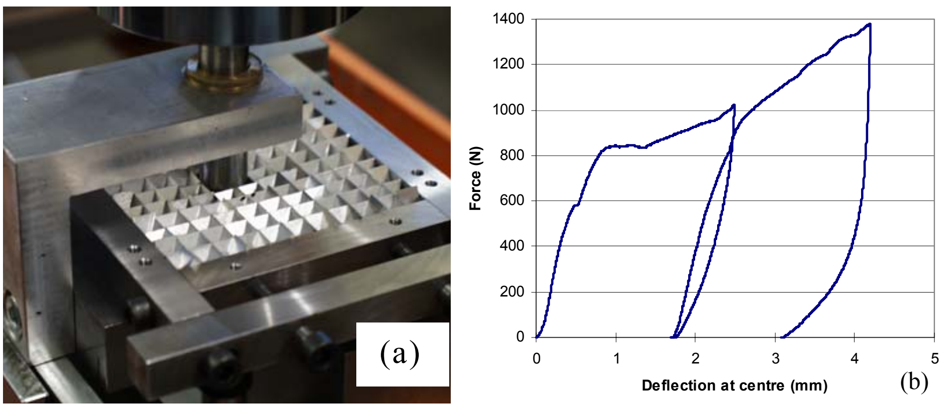

Figure 2. Concentrated loading of the self-locking assembly. Rigid frame restricting the lateral movement of tetrahedrons (a); force vs. deflection diagram for the assembled layer (b).

Figure 2b shows the force vs. central deflection diagram for the assembly. The assembly exhibits two-stage deformation behaviour, with a nearly elastic and an apparently plastic part. As evidenced by the unloading curve, the nearly elastic component is fairly non-linear. A comparison with the results for a massive plate of the same thickness shows [1] that the bending stiffness of the assembly is as low as about one eighth of that of the plate. The residual deformation upon total unloading is very pronounced, but inspection of the individual tetrahedrons, even in the most heavily loaded central part of the structure, showed no sizeable remanent deformation of those. It is to be concluded that the remanent displacement of the tetrahedrons forming a dome-shaped indent is associated with collective behaviour of the assembly, rather than plastic deformation of individual elements.

4. Possible failure mechanisms

The force-deflection diagram (Figure 2b) suggests that the continuation of loading will eventually result in the relative block movement exceeding the block size and final disintegration of the structure. This is an obvious fracture mechanism that involves a very large local strain. Another possibility is related to destruction of separate blocks due to external action (an obvious example being projectile impact). This failure mechanism based on local block fracturing will be addressed here.

Figure 1b shows the top view of a fragment of an assembly. If just one block (e.g. the one marked by white broken line) is removed (that is to say, broken into fragments that cannot be held in place by the adjacent blocks), it will not cause disintegration of the assembly. Therefore, the failure of the assembly should be associated with breakage of a certain number of blocks. Two extreme cases can be considered: (a) *long distance propagation of a crack* initiated in one block and (b) distributed fracturing of blocks caused by an external action such that blocks fail at random and *accumulation of independently broken blocks* can be assumed.

Long distance crack propagation requires growth of a crack generated in a particular block into neighbouring blocks. However, as the blocks are not strongly connected to each other, a mechanism similar to Cook-Gordon retardation [2] should be expected to operate. This mechanism is illustrated in Figure 3 where, for the sake of simplicity, a mode I crack in a fractured block propagating normal to the interface is shown. At a distance r from the crack tip the crack creates normal tensile stress $\sigma_x=K_I(2\pi r)^{-1/2}$ (cf., eg, [2]). As the crack tip approaches the interface, the magnitude of this stress increases eventually becoming sufficient to open part of the interface (if there is no adhesion between the blocks) or create an interface void. This interface void/crack acts to reduce the stress concentration at the tip of the primary crack and, by arresting it, prevents the fracture from propagating into the adjacent block. Therefore, it is the *weak adhesion* of the blocks (or total lack thereof in a single-phased interlocked assembly) that isolates the broken block and preserves the integrity of the assembly.

Accumulation of independently broken blocks will now be considered as a possible mechanism of failure. Since an individual missing or broken block cannot cause failure, the accumulated removed/broken blocks should at least form a connected chain for the assembly to start disintegrating. If one assumes that the blocks are destroyed at random, the failure should be attributed to the concentration of broken blocks reaching the percolation threshold. It is, of course, the 2-D nature of the assembly that permits the use of the percolation theory to model failure (in 3-D an infinite cluster of broken elements or defects could not be associated with failure, since it would not break connectivity of space). In the case under consideration, where the blocks form a square lattice, one has to deal with the so-called site problem [3]. For the site problem on a square lattice, the percolation threshold is 0.59 [3]. Therefore, for the random block fracturing case, around 59% of the blocks need to be destroyed for an assembly to loose its integrity.

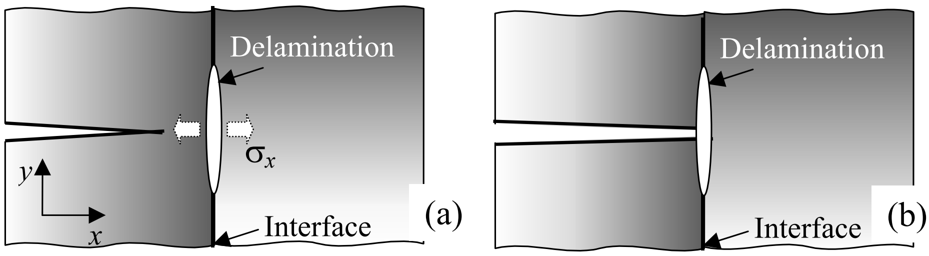

Figure 3. Crack propagation from a fractured block towards the interface (a). The concentration of tensile stress acting in the direction of crack propagation creates an interface crack that eventually arrests the propagation of the main crack (b).

5. Conclusions

The proposed assembly of topologically interlocked tetrahedron-shaped elements forms a layer in which each individual block is held in place by neighbouring blocks. The layer has a low bending stiffness, but can withstand considerable loads even if no binder is used to hold the elements together.

Failure of a single block cannot cause failure of the assembly, as with a single block being damaged interlocking within the assembly is still retained. Weak adhesion between the blocks (or total absence of adhesion) arrests propagating cracks, induced e.g. by impact, and prevents them from spreading into neighbouring blocks. Therefore, the only way to break an assembly is to destroy a certain number of connected blocks. For block fracturing occurring at random and in an uncorrelated way, the total assembly disintegration will require fracturing of about 59% of all blocks. This suggests the suitability of the proposed layers of interlocking elements as shields against impacts.

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