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PRESSING PROBLEMS IN THE MECHANICS OF COMPOSITE MATERIAL STRUCTURES*

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Composite materials are now widely used in various fields of engineering and have become the subject of deep theoretical and practical studies. Their interest stems primarily from their having a set of properties and features which distinguish them greatly from traditional structural materials (metal alloys), and in aggregate provide wide scope both for improving existing structures of the most diverse kinds and for developing new and promising constructional forms and technological processes.

These properties originate first from the characteristics of the initial components in the way of reinforcing elements (fibres, threads, braids, webs) and matrices (polymer, carbon, metal and ceramic), and second, from the so-called effect of synergism, whereby the composition reveals properties not possessed by the individual initial components. The characteristics of the first kind notably include high specific strength and rigidity (with respect to density) of the composites under loading in the direction of reinforcement, due both to the strength and rigidity of the fibres and to the ability of the matrix to ensure their efficient joint operation in taking-up the external load. Of the characteristics of the second kind we may mention the high ductility of composites made from brittle components of low cracking resistance such as glass fibres and epoxide matrix. The existence of the many interfaces, both between the fibres and matrix, and between the individual layers, greatly increases the resistance to brittle fracture and enables materials to be produced in which a high level of static strength is combined with high impact ductility. It may be noted that an increase in the strength of traditional constructional materials is usually accompanied by a decrease in impact toughness.

While the above characteristics determine the main merits of composites, they by no means exhaust their structural properties and scope. Composites based on polymer matrices are notable for high corrosion resistance, while by combining these matrices with organic or glass fibres, materials can be produced with electrical insulation properties and radio transparency, or combinations of polymer or metal matrices with carbon fibres provide electrical conductivity. The low thermal conductivity of most composites means that they can be used without extra protection under conditions of strong short-term surface heating and can act as thermally insulating and protective materials. The high heat resitance of carbonized and ceramic matrices in conjunction with the high strength, rigidity, and heat resitance of carbon fibres provide materials which retain a near-initial level of mechanical characteristics at temperatures exceeding the melting-point of most metal alloys. Compositions based on carbon fibres enable a directional variation of the coefficients of linear expansion to be obtained, so that structures can be produced which retain stability of the geometrical parameters under coditions of cyclical heat action.

In short, composites have a wide range of useful and in some respects unique properties, and by sensibly combining these, efficient structures with very good weight factors can be produced, the development of which is provided for in the Basic Trends of Economic and Social Development of the USSR in 1986-1990, and in the period to 2000. On the other hand, a range of technical problems, including problems of structural mechanics, must be solved in order to realize the great potential inherent in the idea of composite materials and in the properties of their components. It is these problems which we analyse below.

The main feature of composites, viewed as structural materials, is the directional nature of their properties, which can be controlled during manufacture. It is well known that a composite does not usually exist separately from the structure, though efficient automatic technological methods have now been developed (winding, pressing, vacuum and autoclave formation), whereby materials can be obtained with a wide range of mechanical and physical characteristics. In other words, a material can be developed and realized for every structure that most fully corresponds to its function, the field of acting loads, and the conditions of service. In this respect, composites are often similar to natural materials, whose efficiency has often been studied in works on biomechanics.

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In short, the first problem to be considered when treating problems of the mechanics of the structure of composite materials, concerns design methods which provide not only the traditional choice of shape and size of work-parts but also a determination of the type and structure of the composite.

Let us take two examples of the efficient use of composites, on the one hand, in well-developed, and on the other, in promising, constructions. The first class includes equally stressed pressure balloons and vessels, built by the continuous winding method. By sensibly combining a suitable constructional shape, structure of composite, and improved technology, we can obtain constructions whose degree of weight efficiency is 2-3 times better than for metal prototypes. Great attention is at present being paid to the composite pressure balloon, in connection with their possible use as stores for compressed natural gas, mounted in automobiles. Among promising structural elements we may mention inertial energy stores, i.e., flywheels. The efficient utilization in these elements of composites is due to two factors, which follow from the expression $e = k\,(\sigma/\rho)$ for the mass-specific kinetic energy stored in them, namely, the parameter k, which depends on the constructional shape and takes its maximum value of 0.5 for an ideal freely rotating ring, and the specific strength of the material (σ/ρ) under extension. Due to the high specific strength of composites, and the possibility of creating equally stressed disks from them, in which the value of k is close to the maximum value, the specific energy capacity of the composite flywheel is 4-6 times the theoretical value for constructions using traditional materials.

While noting that the theory of optimal reinforcement of composite systems has on the whole reached a high degree of perfection, it must be said that the problem of optimal spatial reinforcing, although scarcely studied, is of great practical importance. While the present methods can control the stiffness and strength of a material in the plane of the layer, the interlayer stiffness and resistance to layer separation depend on the properties of the matrix and are so far little understood. These characteristics can be improved by using spatial (e.g., three-dimensional) systems of reinforcement such as have been proposed in recent years. By developing theoretical, and appropriate constructional-technological, methods, such that optimal spatial reinforcing could be correctly realized in the neighbourhoods of clamping zones of composite elements, points of application of local loads, and cut-outs etc., the field of application of composites could be greatly extended.

Notice also that the basic problems of the theory of optimal design have at present been solved for relatively simple structures such pressure balloons, smooth panels, and shells of revolution. There is a need to further develop complex methods which would provide computer-aided design of complex spatial constructions while simultaneously finding the optimal material structure for the given system of operational forces and the like.

An important stage in the design of any construction, including those made of composites, is verification analysis whereby the chosen design parameters can be justified. Composite materials are well-known to be distinguished by a number of special features, such as anisotropy, lamination, relatively low interlayer stiffness and strength, etc., which together result in much more complex design models. On analysing the vast literature on the design of composite elements, it can be seen that the natural conditions under which the design model and object are suitable do not require that account be taken of all features of the composite behaviour. In particular, the need to take account of transverse deformations and edge effects in thin-walled elements when solving applied problems can be greatly exaggerated.

The stressed state of a thin-walled structure, plate, or shell, is well-known to be divisible into two component states: the basic state, which reduces to linear forces and moments and is satisfactorily described by equations based on the classical or modified hypothesis (e.g., in accordance with Timoshenko's model) of the normal line; and the stressed component state, corresponding to a boundary layer, localized close to the edge. Corresponding to the basic state we have kinematic boundary conditions, which assume that the edge is clamped with respect to its displacements and rotation, independently of the specific constructional method of clamping.

While the class of possible boundary conditions is in principle extended by taking account of the boundary layer, this extension is not great enough for it to be possible to describe the actual nature of the joining of composite elements between one another and with metal elements. Joints of this kind usually contain bolts, rivets, pins, elastic packings, and local reinforcements, while the material may sometimes cease to be continuous and homogeneous or retain the same structure, so that the resulting situation is difficult to formalize and model mathematically. In fact, if account is taken of stresses that are selfbalanced (over the wall thickness), with respect to forces and moments, only a formal refinement is introduced into the design of actual constructions, and the simpler equations which describe only the basic stressed state may be used to solve applied problems. It should be noted that we do not thereby exclude a subsequent more detailed analysis of the joining zones or junctions. By separating such a zone by a section whose distance from the edge spans the domain over which the boundary layer extends, and applying in this section forces and moments corresponding to the basic state, we can study it further in the light of the constructional features of the joining junction by more exact analytical or numerical methods.

Questions concerned with the calculation and design of joints still remain urgent as before. The low strength of composites in the case of cutting and crushing, the adverse effects which arise when fibres are cut through during the formation of mechanical joints, and specific technological methods of obtaining solid joints (preforming and chemical welding) imply a continuous deterioration of bonds and joints in composite constructions. Experience in the successful introduction of composites shows that, when structures are designed in the context of the positive as well as adverse properties of composites, the number of parts and junctions that have to be connected at the final assembly stage is much less than in similar structures made of traditional materials. In spite of these features of composite systems and the fact that there are now well-developed standard adhesion, mechanical, and composite joints, their construction and design still remain one of the main problems in the way of introducing composites into complex hybrid structures.

In conclusion, let us dwell on an important class of non-linear problems of the mechanics of strucutres of composite materials. Until recently, the main design model for analysing composite elements was the model of a linear elastic anisotropic body. The possibility of making wide use of the generalized Hooke's law in the design of composite elements is primarily due to the fact that fibres (which are the main load-bearing elements of a composite) are linearly elastic virtually up to breaking. The physical non-linearity inherent in polymer and metal matrices reveals itself only weakly in the material, since the matrix stiffness is usually small compared with the fibre stiffness. In certain structures, however, e.g., in plates and shells, made of alternate layers of composite with angles of reinforcement $\pm\varphi$, it has been shown experimentally that large (up to 100%) relative deformations can occur, in which the fibres, while virtually undeformed, can change their mutual angles significantly. This effect can be used in particular to develop transformable constructions, made up of semi-finished products (systems of fibres connected by an elastic or not fully set polymer matrix) as a result of supplementary action. It also enables the scope of present technological processes to be greatly extended, since the theoretical reinforcement trajectories and structural shapes can often not be directly realized by traditional methods of winding and laying out.

We have discussed above some problems of the mechanics of composites which in the author's view are of serious interest, both theoretically and practically. While they naturally do not exhaust all the urgent problems of mechanics concerned with composities, at least they partially illustrate the problems that have appeared in recent years in connection with the wide introduction of these promising materials into load-carrying structures.

Translated by D.E.B.