The effectiveness of structures combined from elements of various materials united by bonds consistent with the SSS of the connected elements

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Abstract. Various constructions are considered, combined over sections from various structural materials, such as engineered wood (solid, glued, reinforced, plywood, LVL, CLT, etc.), metal of various grades and alloys, concrete, reinforced concrete, fiber-reinforced concrete, etc., which are combined with the help of various elements (connections) in terms of material, form and work. Examples of various composite structures in which structural elements are connected by bonds of different types are given. The analysis of the pairing of elements of such combined (or composite) structures shows that the most effective structures are those in which the connecting elements are adaptively (self-adapted) aligned with the stress-strain state (SSS) of the mating elements. Following this rule (principle) will allow you to avoid mistakes in the design of combined structures, choose reliable and effective means of connecting structural elements. The same can be attributed to the elements of amplification or reconstruction. A brief description of the patented design with adapted connections installed in two mutually perpendicular planes is given.

1. Introduction
The most effective load-bearing building structures consist of elements (with heterogeneous structural properties and materials), which are interconnected by bonds (compounds) with various properties. At the same time, world experience shows that the effectiveness of such structures is increased if the SSS of the compound is consistent with the SSS of the structural elements themselves. Currently, almost all engineering and design teams are involved in these pressing issues of design and construction [1-5].

Of particular interest are modern building structures made of their glued wood, LVL, CLT and other elements with joints on steel or plastic pins, SPAX screws, glued reinforcing bars, simple tie bolts or other joints [4, 6, 7].

However, generalized recommendations for design and preliminary assessments of the effectiveness of their interaction and rational use in domestic and foreign literature are not enough. Such generalized rules or recommendations are especially useful for structures consisting of heterogeneous building materials with natural or artificial polymorphism, anisotropy, rheonomic and other specific properties.

Currently, modern structures, as a rule, are combined from 3 main structural materials: metal, concrete (stone) and wood. Often, the most critical part of such combined (composite) structures are connections or a “connector” - as an independent structural element that has forms and properties that
differ from the properties of the connected elements of the composite structure. Such a connector can be welding, glue, bolts, anchors, pins, dowels, blind self-tapping screws, glued reinforcing or threaded rods, etc.

There are examples of structural failure in compounds of elements due to the irrational or ineffective use of the properties of the “connector”. This applies to their shape, mechanical properties, assembly conditions and methods, and other parameters. It is noted that some elements of the joints (connectors) in metal, reinforced concrete, wooden or combined structures of them are not always consistent in their own stress states and the effective operation of both the basic elements and the bonded ones. The reliability of such structures is quite low.

2. Methods
In the middle of the last century, the works of the Russian engineer-researcher of wooden structures G Karlsen [8] formulated the "principle of Divisibility" and "principle of Density" for joints of wooden structures. These principles have not yet lost their relevance. The essence of the first principle is that in the joints of wooden elements, it is better to put a lot of small connections than one "big" connection, even if they have the same load-bearing capacity. This allows you to avoid stress concentration and disperse the points of force transfer to an enlarged area of the connected elements. The reliability of this connection increases significantly. The second principle is currently also relevant, mainly for wooden structures made of sawn boards or solid beams and logs. And for modern glued wooden elements, the principle is fully implemented.

Later in the works of the Russian engineer E Serov [9] for modern wooden structures, the "principle of tracking orientation" was proposed, which for anisotropic solids was reformulated by E Ashkenazi [10] as "the Principle of coaxiality of the stress tensor and the strength tensor". The essence of this principle is to coordinate the anisotropy of the strength of wood and the stress state of the wooden structure. An example of the manifestation of this principle is a polyline glued beam (Figure 1), in which the coupling in the center to the toothed one is significantly less reliable than a bent-glued beam (Figure 2) with reinforcement in the direction of radial stretching.

Other examples of the very unsuccessful use of the properties of the LVL material are also known (Figure 3), where the inconsistency of the SSS structure with the anisotropy of the LVL strength leads to structural failure (Figure 4). This is an example of a failed (incompetent) use of LVL properties.
The above principles are certainly true, but applicable to individual solid deformable bodies (elements) that are not connected in a combined design. In them, in essence, it is said about the coordination of the polymorphic properties of the material with its stress-strain state. For example, a concrete element certainly works better in compression than in tension or bending, and a plywood sheet works more effectively in tension if the tensile force is directed along the outer layers of plywood. This means that the structure of the material should be oriented taking into account the vector of internal structural forces. Currently, the reinforcement of wooden structures using steel or non-metal reinforcement is actively used or the strengthening of sections of wooden structures with the help of modifications [11-13].

However, quite often for reasons of oversized dimensions, transportation or installation difficulties, glued wooden structures are made in separate parts (assembly units), which are subsequently assembled at a construction site into a single structure. The assembly process is carried out according to a special project using various connecting elements, which should conditionally transfer SSS from one assembly element to another assembly element. At the same time, the design of the connecting element must be adapted to the connected elements both in terms of stress state and reliability (efficiency).

3. Results and Discussion

Figure 5, 6 and 7 show examples of pairing of structural parts with varying degrees of adaptive consistency of the SSS of the connected elements and the connection itself.

Figure 5 - 1 (left) shows a well-known composite wooden beam on pliable ties in the form of transverse dowels made of hardwood in which the fibers are arranged vertically. Figure 5 - 2 (right) shows the same design, but with the glued or screwed rods installed at an angle.

In the first embodiment, the oak dowel plate is used for bending, and in the second embodiment, the installed rods work mainly in tension, since in their SSS (tension) they correspond to the direction of the main tensile stresses. In addition, in the second embodiment, the rods are directed toward the “main” tensile stresses arising in the beam. Thus, even with the same bearing capacity of these options, the deformability of the 2nd option will be less, and the efficiency and reliability is higher compared to the 1st option.
Figure 6. Two options for solving the rigid joint of compressed-flexible structural elements. 

Figure 6 shows two options for the rigid joint of the connected parts of the structure, which works in compression with bending. In both the 1st and 2nd variants, the connecting elements perceive the compressive and tensile forces in the respective zones. However, in the first embodiment, in the stretched zone, vertical steel rods work on bending, wood - on cracking and crushing. In this case, in the compressed zone, these elements may not work at all and are used in case of reverse bending moment or during mounting loads. In addition, the bending of a cylindrical steel dowel and the work of wood for splitting and crushing do not have their own high strength characteristics. A knot of such a construction can hardly be called rigid, since the pins are malleable joints. In addition, embedded horizontal steel plates weaken the cross section of the wooden element. And vice versa, in the 2nd variant [14] the glued rods work in tension, do not create shearing and crushing stresses in the holes, and harden the inner areas of the wood around the nails with adhesive. Such a constructive solution is the most rational, since it observes SSS consistency of structural elements with communication elements.

Figure 7 also shows two options for solving the connection node of structural elements from bamboo [15], in which the task of connecting the main bamboo rods is solved differently. The option on the right is preferable, since it respects the mechanical properties of bamboo and metal elements with their SSS of the entire structure under operating loads.

Figure 7. Options for pairing bamboo core elements in 3D image.

As a result of studies of various structures combined from various materials, SPBGASU experts in the field of structures made of wood and plastic came to the conclusion that the effectiveness of composite combined structures is increased if the SSS of the “connector” is adapted or is consistent with the SSS of the connected elements. Thus, the principle of Adaptive Matching of Connectors.
with Elements of a composite structure (conditionally AMCE) was formulated, which gives a general recommendation for the design of effective composite structures.

The above examples of applying the AMCE Principle have one feature, which is that the connections and connected elements are located and work only in one or several parallel planes (surfaces), usually vertical. Cross-sections of such structures, consisting of a combination of plywood, LVL and glued wood, are shown in Figure 7. These structures are composite not only in the plane of the main internal forces (vertically), but also in the planes inclined or perpendicular to it, then there are shear deformations between these elements. In such cases, adhesive joints are arranged or blind plugs (nails, self-tapping screws, etc.) are installed perpendicular to the shear plane. Shear forces arise in the bonds, which create bending stresses in the pins, and shear stresses in the adhesive joints, which can cause breaking fractures along the glue line.

Figure 7. I-section or box-shaped sections from combinations of plywood, LVL and glued wood.

In accordance with the ACC principle, self-tapping screws should be installed between the belts and walls in order to perceive shear forces in two mutually perpendicular planes: in the horizontal XY for perceiving the horizontal component at an angle of 45° to the X axis, and in the XZ plane at an angle corresponding to the angle of inclination main tensile stresses in the wall (Figure 8). Two problems were simultaneously solved here: the first was to make the self-tapping screws work in tension along the direction of the main tensile stresses in the wall, and the second was to connect the belts to the wall so that the belts deform equally with the wall by means of self-tapping screws [16-19].
Figure 8. Composite box-shaped structure with ties (self-tapping screws) installed in 2 X-Y and X-Z planes.

4. Conclusion

Six experimental beams were made and tested from a span of \( L = 6.4 \) m and a section height of \( h = 50 \) cm (\( L / h = 1 / 12.8 \)). Of which 3 pcs. box section and 3 pcs. I-section. The load was applied in the form of 8 forces, which is approximately equivalent to a uniformly distributed load. The first results showed that the tested designs have great rigidity (low deformability). The destruction of all beams was brittle (non-ductile) in nature and occurred "along the wood" in the reference zones from shear stresses in the wall. This indicates a sufficient margin of safety of the wall and belt joints on stretched self-tapping screws.

In order to further verify the operability of the proposed principle, the following tasks were set:
- search and substantiation of arguments for rational adaptation of connectors for structures composed of various structural materials;
- analysis (SSS) of structures composed of various structural materials and the search for different connectors of structures most adapted to SSS under various influences on them;
- development of unified design solutions for connectors between elements of complex structures in engineering systems, taking into account the effectiveness of the accepted connections and the consistency of their SSS;
- conducting experimental studies of known or creating new designs with compounds adapted to the SSS of the elements of these structural;
- the creation of specific methods of calculation, design, installation and operation of structures with adapted connections.
- reduction of material consumption, labor intensity and cost of complex structural solutions in construction, engineering, etc.

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