Computational Studies of Connections of Spatial Composite Structures of Space-Rocket Techniques

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Abstract

Objectives: Actuality of the study is determined by a number of technical optimization problems due to singularity of designed objects in creation of large space structures. A characteristic feature of such problems is a combination of requirements for increasing of dimensions and providing sufficient stiffness and reliability in response to minimum mass optimization of load-bearing structure weight. This article discusses the combination of such details of construction as metal bushing and carbon tube by means of a heat-resistant polyurethane adhesive VK-20 modified by carborane compounds. Studies consist of calculation of stress-strain state of adhesive joint to determine the shear and breaking stresses in the contact area between the bonding parts. Assessment of failure-free operation of adhesive joint is also conducted during these studies. Methods: Computational studies of connections for manufacture of spatial composite structures of rocket and space techniques have been conducted by finite element analysis. Findings: Simulation of stress-strain state and assumptions adopted during simulation were described. Improvements: Calculations of stress-strain state have been conducted for model of spatial composite structure of space-rocket techniques.

Keywords: Adhesive Joint, Carbon Fiber Composite, Finite Element Mesh, Space-Rocket Techniques, Stress-Strain State, Transformable Antenna

1. Introduction

Future development of radio astronomy, solar energy and space communication, investigation of the earth surface and other planets from space nowadays directly associated with possibility of space launch of large structures of different type and assignment. Creation of large space structures is associated with the solution of a number of technical optimization problems, due to the uniqueness of designed objects. One of important and rapidly developing directions in the area of space structures creation is a development of large transformable antennas for space communication, mounted on spacecrafts of different assignment. Some of such structures include expandable systems, which are assembled from load-bearing and fastening elements which help to combine parts of load-bearing structure together, not preventing at that deployment kinematics of transformable antenna.

The object of the study is a connection of primary structure of transformable antenna, which consists of carbon fiber tubes and metal bushings. To ensure the necessary rigidity and efficiency of the joint design, connection of bushing and tube is carried out by adhesive joint. Heat-resistant polyurethane adhesive VK-20 modified by carborane compounds is selected as adhesive component. Distinctive feature of this adhesive is its high heat resistance of 10,000 hours at temperatures up to 300°C, at 400°C adhesive joints provide durability for 500 hours and at 800°C they provide a short-term durability. At temperatures up to 200°C as the primary adhesive material organic component acts, at higher temperatures (200-400°C) the processes of its thermal decomposition begin, forming coke, which also has good adhesive properties and particularly coke provides the durability of the adhesive joint at temperatures above 400°C.

A huge number of researches are conducted in the
field of polyurethane adhesives, directed to various spheres of human activity. There are studies aimed at study of deformations, resulting from internal stresses in composite membrane with a metal glue used as the adhesive layer, with tests carried out in the temperature range of 150-350°C.7 Researches in the field of reliability of polyurethane adhesives at cryogenic temperatures of -150°C with addition of chopped fiberglass roving to adhesive for its viscosity increase are also known.8 Some studies present data on bonding strength of adhesives, which contain acrylic and epoxy groups, at temperature of -196°C and data on influence of long exposition of single-component polyurethane adhesive at temperature of 70°C on its ageing resistance.9 Models of laminates glued with a concrete base exposed to high temperatures were considered as well as many investigations are aimed at studying the behavior of adhesive at temperatures of 20°C, 0°C and -40°C in laminated beams and various kinds of products related to gluing of wood.10

2. Concept Headings

Computational studies of connections of spatial composite structures of rocket and space techniques are conducted with the help of engineering review by finite element analysis.

Engineering review represents a complex of tests, designed for assessment of ability of equipment, structures and also products produced to bear a project load and to work at rated duty.

In modern design various program packages of Computer-Aided Engineering (CAE) are widely used, which allow to conduct engineering review of computer models without real experiments.

CAE is a common name for programs and program packages designed for solution of different engineering tasks: calculations, analysis and simulation of physical processes. Calculation part of program packages typically is based on numerical computation of differential equations (finite element analysis, finite volume method, finite difference method, etc.).

CAE systems represent a variety of program products, which allow assessing with the help of calculation methods how the product computer model will behave under actual operating conditions. These systems help to ensure product working capacity without heavy spending of time and money.

Most common and effective calculation method, applied in CAE systems is a Finite Element Analysis (FEA). Systems which use FEA as numerical analysis of technical constructions are called FEA systems.

Modern CAE are used together with CAD systems and often are integrated in them. In this case they are called hybrid CAD/CAE systems.

Overview of FEA

Analysis by FEA starts with digitalization of the region of interest (task area) and its compartment into cells of a mesh. Such cells are called finite elements (FE).

FE may have different shape. In contrast to real construction FE in discrete model are connected together only in isolated points (nodes) determined by finite amount of nodal parameters.

Selection of suitable elements with necessary amount of nodes from the library of accessible elements is one of the most important decisions for a user of FEA package. Designer also must set a total amount of elements (their size in other words).

FEA classical form is known as $h$-version. Piecewise polynomials of constant degrees are used in this method as a shape function and accuracy is increased through decrease of the cell size. The $p$-version uses a fixed mesh and accuracy is increased through increase of the shape function degree. Common rule is that the more amount of nodes and elements ($h$-version) or the higher shape function degree ($p$-version), the solution is more accurate, but more expensive from calculation point of view.

The next step is assembling. Assembling is a combination of individual elements into finite element mesh. From a mathematical standpoint assembling consists in assembly of rigidity matrixes of single elements into one global rigidity matrix of entire construction. In this case two numbering systems of element nodes are fundamentally used: local and global. Local numbering is a constant nodal numbering for each type of FE in accordance with introduced local coordinate system on the element. Global nodal numbering of entire construction may be absolutely random, as well as global numbering of FE. However one-to-one correspondence exists between local numbers and global numbers of nodes, on the basis of which global system of finite element equations is formed.

Approximation

FEA refers to discrete analysis methods. However in
contrast to numerical methods based on mathematical digitalization of differential equations, FEA is based on physical digitalization of object being examined. Real construction as continuous medium with a lot of infinite number of degrees of freedom is replaced by discrete model of interconnected elements with finite number of degrees of freedom. Since possible number of discrete models for continual region is infinitely large, the major task consists in selection of the model that approximate this region best of all.

Subject matter of continuous medium approximation by FEA is as follows:

- Region of interest is divided into certain number of FE and family of elements across the region is named the system or FE mesh;
- It is expected that FE are connected together in finite number of points – nodes, situated along the outline of each FE;
- Polynomial approximant is set for each FE.

Approximating functions:

Polynomial approximant for one-dimensional FE:

\[ u(x) = \sum_{i=0}^{n} a_i x^i \]

Example for one-dimensional FE:

![One-dimensional FE example](image)

Polynomial approximant of the second order:

\[ u^2(x, y) = \beta_1 x + \beta_2 y + \beta_3 x^2 + \beta_4 xy + \beta_5 y^2 \]

Polynomial approximant degree defines number of nodes for each element. It should be equal to the number of unknown coefficients \( \alpha_i \) included into polynomial.

Required functions within each FE (for example, distribution of displacements, deformations, strains, etc.) are expressed with the help of approximating functions through nodal values, which represent main unknown FE.

Required approximating function:

\[ u(x) = \sum_{i=0}^{n} h_i(x) q_i \]

Where: \( h(x) \) = co-ordinate / basic functions, so called shape function; \( q \) = unknown coefficients (nodal values).

In matrix view:

\[ \hat{U}(\hat{x}) = \hat{H} \hat{U} \]

Approximation usually gives approximate but not exact description of real distribution of required values in the element. Because of that the results of structural analysis in the general case are also approximate. Naturally a question of accuracy, stability and convergence of solutions, obtained by FEA may be posed.

Accuracy is understood as deviation of approximate solution from accurate or true solution. Stability first of all is defined by error growth while performing certain computing operations. Unstable solution is a result of the wrong choice of approximating functions, “bad” region dividing, incorrect representation of the boundary conditions, etc. Convergence is understood as gradual approximation of successive solutions to ultimate solution as long as parameters of discrete model are determined, such as element dimensions, degree of approximating function, etc. In this regard the concept of convergence is similar to the meaning that it has in usual iteration processes. Therefore in converging procedure difference between consequent solutions is decreased, approaching zero at the extreme.

Abovementioned concepts are illustrated in Figure 1. Herein \( x \)-axis defines degree of clarification of parameters of discrete model, and \( y \)-axis defines approximate solution obtained at that clarification. In the figure the monotonic type of convergence is shown, at which solution accuracy is smoothly increased.

![Figure 1](image)
Computational Studies of Connections of Spatial Composite Structures of Space-Rocket Techniques

Figure 1. Dependence of solution from parameters.

Setting of boundary conditions and material

After task area approximation by the set of discrete finite elements we should define materials characterization and boundary conditions for each element. With the indication of different characteristics for different elements, we can analyze behavior of an object composed of different materials.

According to terminology of mathematical physics that considers various differential equations describing physical fields from unified mathematical point of view, boundary or edge conditions for given differential equations are divided into two basic types: essential and natural. Usually essential conditions are imposed on required function and natural ones are imposed on its spatial derivatives.

From the standpoint of FEA essential boundary conditions are such that shape the model degrees of freedom and are imposed upon components of global vector of unknown \( U \) (displacements). Alternatively natural boundary conditions are such that indirectly influence on degrees of freedom through the global system of finite-element equations and are imposed on right part of the system – vector \( F \) (applied forces).

As a rule essential boundary conditions in mechanical tasks are such that include displacements (but not deformations, representing space derivative of displacements). According to terminology of the theory of elasticity such boundary conditions are known as kinematic. For example, embedding and hinge support in rod tasks are essential or kinematic boundary conditions, imposed on a bend or longitudinal displacements of the rod points. Notice that in rod bending tasks essential boundary conditions are also conditions, imposed on a first derivative of the rod bending on axial coordinate that has mechanical sense of angle of the rod rotation.

The same may be said about angle of rotation in the plate bending theory.

Natural boundary conditions in mechanical applications of FEA are conditions, imposed on different external force factors affecting points of the body’s surface – concentrated forces and moments in rod tasks, distributed forces in two-dimensional and three-dimensional tasks. Such restrictions are called force boundary conditions.

Mixed boundary conditions are widely used in setting objectives of continuum mechanics particularly in the theory of elasticity. It means that some components of displacements and surface forces are simultaneously set in this point of the body's surface.

Three enumerated variants of boundary conditions are the most widespread in pure mechanical applications of FEA.

Besides boundary conditions for resolving of equations it is necessary to set characterization of material of which research object is made. For example, in stress-strain analysis parameters determine connection of stress and deformation.

System of equations forming

After set up of the boundary conditions and material, FEA program forms a system of equations, connecting the boundary conditions with unknowns, whereupon solve the system against unknowns.

Result generation

After finding of values of unknowns user gets a possibility to calculate value of any parameter in any point of any FE by the same required function that was used for system of equations forming. FEA program outputs are usually presented in a numerical form. However it may be difficult to get general picture about behavior of corresponding parameters from numeric data. Graphic images are more informative usually, because they give an opportunity to study behavior of parameters over the whole task area.

FEA formulation

By means of getting basic, i.e. resolving equations, there are four main kinds of FEA: direct, variational, weighted residuals and energy balance. Among enumerated kinds of FEA variational method and weighted residuals Galerkin method are particularly topical in structural mechanics.

Let us consider the variational method. This method is based on stationary principle of some variable that
depends on one or more functions (such variable is named functional). In respect to mechanics of deformable solids this variable represents potential (Lagrangian functional) or additional (Castigliano’s functional) energy of the system or is formed on the basis of these two energies (Hellinger-Reissner and Hu-Washizu functionals). If substitute approximating expressions of the required functions into functional and apply extremum principles (accordingly Lagrange principle, Castigliano’s principle, etc.) to it, we will get the system of algebraic equation, the solution of that will be values of nodal unknowns.

Variational Lagrange principle: potential energy acquires stationary values on kinematically admissible displacements, which satisfy specified boundary conditions and force equilibrium conditions.

In contrast to direct method, variational method can in equal measure be successfully applied to both simple and challenging tasks.

So let us consider three-dimensional object of arbitrary shape, being in equilibrium condition affected by some stress load (Figure 2). Let us denote friction forces affecting the surface (surface forces) by \( p \), and mass forces (volume forces) – by \( G \). In general these forces are laid out on components parallel to the axes of coordinates:

\[
G = \begin{bmatrix}
G_x \\
G_y \\
G_z
\end{bmatrix},
p = \begin{bmatrix}
p_x \\
p_y \\
p_z
\end{bmatrix}
\]  

(1)

Figure 2. Three-dimensional object with external forces.

Let us denote displacement of arbitrary point of the object \((X,Y,Z)\) in comparison with configuration in absence of stress load by symbol \( U \). In this case

\[
U^T = [U(X,Y,Z) \cdot V(X,Y,Z) \cdot W(X,Y,Z)]
\]  

(2)

Displacements \( U \) will lead to occurrence of deformation

\[
\varepsilon^T = [\varepsilon_{XX} \cdot \varepsilon_{YY} \cdot \varepsilon_{ZZ} \cdot \varepsilon_{XY} \cdot \varepsilon_{YZ} \cdot \varepsilon_{ZX}]
\]  

(3)

and relevant strains

\[
\sigma^T = [\sigma_X \cdot \sigma_Y \cdot \sigma_Z \cdot \tau_{XY} \cdot \tau_{YZ} \cdot \tau_{ZX}]
\]  

(4)

It is necessary to calculate \( U, \varepsilon, \sigma \) in the point \((X,Y,Z)\) with respect to preset external forces. Total potential energy of elastic body is described by expression:

\[
\Pi = \vartheta - A - \frac{1}{2} \int \varepsilon^T \sigma dV - \int \frac{\tau^T \sigma dV}{\varphi} - \int \frac{\varepsilon^T \varepsilon dV}{\varphi} - \int p \cdot dS
\]  

(5)

Where \( \vartheta = \) energy of deformation;

\( A = \) work of applied mass and surface forces.

Three last items of equation (5) describe the external work, executing by real forces \( G, p \) on virtual displacements \( \overline{U} \).

A superscript \( S \) of vector \( \overline{U} \) means virtual displacement on the surface. Strains are calculated through deformations by relevant constitutive equations.

Let us obtain FEA equations from equation (5), starting with approximation of the object represented in Figure 2 by FE mesh. Elements are connected together in nodal points which are located on their boundaries. Displacement in any point with coordinates \((x, y, z)\) in the local coordinate system of element is considered a function of displacements in nodal points.

So for the element \( T \) assumption is declared that

\[
u^s(x,y,z) = H^s(x,y,z)\overline{U}
\]  

(6)

Where \( H = \) interpolation displacement matrix (shape functions), \( \overline{U} = \) vector of displacement on all nodes. If total amount of nodes is equal \( N \), vector \( \overline{U} \) is written as follows:

\[
\overline{U}^T = [u_1 u_2 u_3 u_4 u_5 u_6 u_7 u_8 u_9 u_{10}] 
\]  

(7)

This expression can be rewritten as:

\[
\overline{U}^T = [U_1 U_2 \ldots U_n]
\]  

(8)

Although displacements of all nodes are specified in equation (8) and therefore these displacements are also included into expression (6), for each certain element internal displacements are determined by displacements in its nodes only. All nodes have entered into expression (6) because it facilitates the process of combination of matrix of single elements into matrix of structure in whole, as it will be shown below.

Equation (6) allows calculating of deformations:
\[ \varepsilon^{(m)}(x,y,z) = \mathcal{B}^{(m)}(x,y,z) \mathbf{U} \]  

(9)

Rows of a matrix deformations-displacements \( \mathcal{B}^{(m)} \) from equation (9) are obtained by differentiation and combination of matrix rows \( \mathbf{H}^{(m)} \).

Now we can also write expressions for strains inside each element:

\[ \sigma^{(m)} = C^{(m)} \varepsilon^{(m)} + \sigma_0^{(m)} \]  

(10)

Where \( C \) = flexibility matrix of element \( T \) (Hooke matrix), \( \sigma_0^{(m)} \) = initial strain inside the element. In structure of different elements it is possible to preset own flexibility matrix for each of them.

Let us rewrite equation (5) in view of sum over the volume integrals and integrals over the surfaces of single elements:

\[ \Pi = \sum m \left[ \frac{1}{2} \sum \mathbf{B}^{(m)T} \mathcal{C}^{(m)} \mathbf{B}^{(m)} dV^{(m)} - \sum \int H^{(m)} \mathbf{U}^{T} \mathbf{G}^{(m)} dV^{(m)} - \sum \int \sigma_0^{(m)} \mathbf{B}^{(m)T} \mathbf{U}^{T} dV^{(m)} \right] \]  

(11)

Where element \( T \) varies from 1 to total amount of elements in the system.

Substitution of (6), (9) and (10) into (11) will give the next expression:

\[ \sum m \Pi^{(m)} = \frac{1}{2} \sum \mathbf{B}^{(m)T} \mathcal{C}^{(m)} \mathbf{B}^{(m)} dV^{(m)} + \sum \frac{1}{2} \int \mathbf{H}^{(m)} \mathbf{U}^{T} \mathbf{G}^{(m)} dV^{(m)} - \sum \sigma_0^{(m)} \mathbf{B}^{(m)} dV^{(m)} \]  

(12)

Where surface interpolation matrixes of displacements \( \mathbf{H}^{(m)} \) are obtained from volume interpolation matrixes of displacements \( \mathbf{H}^{(m)} \) by substitution of coordinates of element surface.

Let us denote

\[ \mathbf{K} = \sum \int \mathbf{B}^{(m)T} \mathcal{C}^{(m)} \mathbf{B}^{(m)} dV^{(m)} \]  

(13)

\[ \mathbf{R} = \mathbf{R}_S + \mathbf{R}_D - \mathbf{R}_0 \]  

(14)

\[ \mathbf{R}_S = \sum \int \mathbf{H}^{(m)T} \mathbf{G}^{(m)} dV^{(m)} \]  

(15)

\[ \mathbf{R}_D = \sum \int \mathbf{H}^{(m)T} \mathbf{p}^{(m)} dS^{(m)} \]  

(16)

\[ \mathbf{R}_0 = \sum \int \sigma_0^{(m)} \mathbf{B}^{(m)T} dV^{(m)} \]  

(17)

Energy minimization \( \Pi \) results in equation:

\[ \frac{\partial \Pi}{\partial \mathbf{U}} = \frac{\partial}{\partial \mathbf{U}} \sum m \Pi^{(m)} = 0 \]  

(18)

which with account of introduced notations will be written as:

\[ \mathbf{K} \mathbf{U} = \mathbf{R} \]  

(19)

Note that summing of integrals taken over volumes of single elements in formula (14) expresses the fact that rigidity matrix of set of elements as a whole is obtained by addition of rigidity matrix of elements \( \mathbf{K}^{(m)} \). Similarly vector \( \mathbf{R} \) of volume force, affecting the whole body, is obtained by summing of volume force vectors, affecting separate elements. Vectors of other forces are calculated in the same way.

The expression (19) describes static equilibrium. When applied forces are varying with time, this expression is applicable to any certain moment. However on rapid loading inertial forces must be considered.

On the d’Alambert’s principle inertial forces of single elements may be added to mass forces. If we assume that acceleration in any point of the element is connected to acceleration in nodal points by matrix \( \mathbf{H}^{(m)} \) alike displacements, input of mass forces into force vector \( \mathbf{K} \) will be expressed as:

\[ \mathbf{R}_S = \sum \int \mathbf{H}^{(m)T} \left[ \mathbf{G}^{(m)} \mathbf{U} - \mathbf{H}^{(m)} \mathbf{U} \right] dV^{(m)} \]  

(20)

Where \( \mathbf{U} \) = accelerations in nodal points, and \( \rho^{(m)} \) = mass density of element \( T \).

Substitution of (20) instead of (15) into (19) will give a new equilibrium equation:

\[ \mathbf{M} \ddot{\mathbf{U}} + \mathbf{K} \mathbf{U} = \mathbf{R} \]  

(21)

Where \( \mathbf{M} \) = mass matrix.

Note that \( \mathbf{U} \) and \( \mathbf{R} \) in equation (21) are time functions.

Damping forces may be taken into account as additional input into mass forces, that allow describing damping effect (attenuation). In this case the equation (20) takes a new form:

\[ \mathbf{R}_S = \sum \int \mathbf{H}^{(m)T} \left[ \mathbf{G}^{(m)} - \mathbf{p}^{(m)} \mathbf{H}^{(m)} \mathbf{U} - \mathbf{K}^{(m)} \mathbf{H}^{(m)} \mathbf{U} \right] dV^{(m)} \]  

(22)

Where \( \dot{\mathbf{U}} \) = velocity vector of nodal points, and \( k^{(m)} \) = damping coefficient for element \( T \).

The equilibrium equation takes the form of

\[ \mathbf{M} \ddot{\mathbf{U}} + \mathbf{C} \dot{\mathbf{U}} + \mathbf{K} \mathbf{U} = \mathbf{R} \]  

(23)

Where \( \mathbf{C} \) = damping matrix.

In practice matrix \( \mathbf{C} \) is usually constructed from mass matrix and rigidity matrix on the grounds of experimental
data on damping in material, because it is quite difficult to define damping parameters of single elements.

Further the order of simulation of stress-strain state of connection model is described.

Studies involve calculation of stress-strain state of adhesive joint to determine the shear and fracture stress in the contact area between bonding parts.

2.1 Simulation of the Stress-Strain State of Connection Model

Thermal loading that imitates temperature loading, which structures experience in outer space, was accepted as a reason of deformation.

The stress-strain state of adhesive joint was considered in quasi-static approximation at the temperature change from minus 120°C up to plus 150°C.

In the simulation of stress-strain state the following assumptions were accepted:

- The materials used were considered solid, homogenous and indestructible;
- Chemical composition and physical state of materials were considered unvaried in the process of analysis;
- Physical characteristics such as density, thermal coefficient of linear expansion (TCLE), elasticity modulus, Poisson's ratio, heat capacity and thermal conductivity were assumed constant without consideration anisotropy of properties of specified materials.

Average properties of carbon fiber composite on the basis of carbon fiber M46J Torayca and epoxy-chlorodiane modified resin ECD-MD were specified for tubes. Material properties of nickel-iron alloy 36N were defined for metal bushings. Basic materials employed and their specified properties are presented in Table 1.

Table 1. Thermophysical properties of basic materials employed

| No. | Name of parameter                  | Material                  |
|-----|-----------------------------------|---------------------------|
| 1   | Density, kg/m³                    | 36 N, Carbon fiber composite |
| 2   | Specific heat capacity, J/(kg·K) 10³ | 0.50, 1.12               |
| 3   | Thermal conductivity, W/(m·K)     | 12, 30                   |
| 4   | TCLE, s⁻¹·10⁶, K⁻¹                | 1.2, 0.17                |
| 5   | Poisson's ratio                   | 0.30, 0.31               |
| 6   | Elasticity modulus, MPa, 10⁴     | 15.00, 12.00             |

2.3 FE Mesh Building

In the process of solution FE mesh was built with the help of built-in adaptive method of the mesh control. The element size of this mesh is 2.00 mm. As example of graphic image of FE mesh building by adaptive method, a connection model of carbon fiber tube of size 185×20×20 mm and metal bushing was selected (Figure 3). The number of FE of the resulting meshes is equal to 16690.

2.3 Calculation of stress-strain state of connection model

Material from table 1 was specified for connection model and a mesh generated in it, and then a load was applied corresponding to the computational scheme shown in Figure 4.

Figure 3. FE mesh built by adaptive method in the volume of connection model of metal bushing and carbon fiber tube of nominal size 185×20×20 mm.

Figure 4. Computational scheme of connection model of carbon fiber tube and metal bushing.

3. Results

The results of calculations are maximum and minimum fracture and shear stresses in the contact area of external
surface of the bushing and internal surface of the tube. Comparative tables 3 and 4 show maximum and minimum stresses in the bushing and tube contact area under impact of temperatures of -120°C and +150°C. Figures 5-7 present connection model of carbon fiber tubes of nominal size 185×20×20 mm as example of graphical image of fracture and shear stresses in the tube and bushing contact area.

Table 2. Stress-strain state of connection model at temperature of +150°C

| No. | Name of parameter     | Value   |
|-----|-----------------------|---------|
| 1   | Fracture stresses, Pa | max 1.36·10⁷ |
|     |                       | min -7.30·10⁷ |
| 2   | Shear stresses, Pa    | max 3.63·10⁷ |
|     |                       | min 0     |

Table 3. Comparative table of stress-strain state of matrix models at temperature of +120°C

| No. | Name of parameter     | Value   |
|-----|-----------------------|---------|
| 1   | Fracture stresses, Pa | max 1.36·10⁷ |
|     |                       | min -7.30·10⁷ |
| 2   | Shear stresses, Pa    | max 3.63·10⁷ |
|     |                       | min 0     |

Fracture stresses in connection models at temperature of +150°C

Figure 5. Fracture stresses in connection model of metal bushing and carbon fiber tube of nominal size 185×20×20 mm.

Shear stresses in connection models at temperature of +150°C

Figure 6. Shear stresses in connection model of metal bushing and carbon fiber tube of nominal size 185×20×20 mm.

Shear stresses in connection models at temperature of -120°C

Figure 7. Shear stresses in connection model of metal bushing and carbon fiber tube of nominal size 185×20×20 mm.

Under impact of high temperatures two types of processes proceed simultaneously in relevant adhesive materials: slow and rapid.

Slow processes of adhesive degradation are implemented during many years of operation in the form of natural aging (degradation) without intensive external impact and usually have a linear character. Such change in properties of adhesive material is named heat resistance,
and for determination of heat resistance Martens, Vicat, etc. temperature methods are used.

Rapid processes generally associated with thermal decomposition of adhesive, which is irreversible and has a nonlinear character. Such change of properties is named thermal stability, and for its determination thermoanalytical techniques are used.

Therefore during calculation of reliability factors, characteristic of adhesive strength is considered as not one but two separate factors with correlation between them functionally dependent upon one and the same impact of temperature in this case.

Usually in calculations of reliability of such systems the condition of independence of implemented factors is accepted, but calculation data of failure-free operation probability and lifetime are greatly reduced. For obtaining of reliability characteristics, more close to their true value, the analytical dependencies between factors, determining performance of compounds that take into account functional relationship with parameters of external impact, are proposed.

It is suggested to approximate processes of heat resistance reduction, where slow adhesive strength degradation also takes place, by the linear dependencies:

\[ \tau_2(t_i) = \tau_0 - \gamma t_i \]  

Where \( \tau_1(t_i) \) is an average value of breaking stress in adhesive joint with a current time \( t \) under conditions of adhesive chemical decomposition at elevated temperatures; \( \tau_0 \) is an average value of initial strength at zero time \( (t = 0) \); it is characteristics of degradation, which determines the speed of adhesive strength reduction.

In Figure 9 duration of temperature exposure is measured in years. The value of lifetime (point A) is determined upon condition of known values of maximum acceptable stress \( \tau_{lim} \) below which adhesive strength cannot go down.

Both these characteristics \( \{\tau_1(t_i) \text{ and } \tau_2(t_i)\} \) are conditions, but it is handy to use them for comparisons of estimates between different types of adhesives.

Assessment of the level of \( \tau_1(t_i) \) by conditions of thermal decomposition for time \( t_i \) and \( t_{i+1} \) is performed at fixed temperatures by equation (24). Similarly, for the same time sections on the basis of dependence (25) calculations of \( \tau_2(t_i) \) and \( \tau_2(t_{i+1}) \) are performed.

Determining the level of probability of failure-free operation in the case of independent behavior of thermal destruction of adhesive and gradual reduction in its heat resistance come down to probability estimates of thermal destruction of adhesive and gradual reduction in its heat resistance.
probability of failure-free operation \( P_1(t_i) \) for specified time section \( t_i \) is performed by dependence:
\[
P_1(t_i) = \Phi\left(\frac{[\tau_1(t_i) - \bar{\tau}_1(t_i)]}{\sqrt{\sigma_{[\tau_1]}^2 + \sigma_{[\tau_2]}^2}}\right).
\] (26)

Assessment of probability of failure-free operation of adhesive joint by conditions of loss of heat resistance \( P_2(t_i) \) is performed for the same time section and is determined on the basis of similar expression:
\[
P_2(t_i) = \Phi\left(\frac{[\tau_2(t_i) - \bar{\tau}_2(t_i)]}{\sqrt{\sigma_{[\tau_1]}^2 + \sigma_{[\tau_2]}^2}}\right).
\] (27)

where \( \{\tau_j\} \) and \( \{\tau_j\} \) are acceptable values of breaking shear stresses in adhesive joint by conditions of thermal destruction and loss of heat resistance respectively; \( \tau_j(t_i) \) and \( \tau_j(t_i) \) are actual stresses in adhesive joint at time \( t_i \) in conditions of thermal destruction and loss of heat resistance respectively; \( \sigma_{[\tau_1]} \) and \( \sigma_{[\tau_2]} \) are the standard deviations of true values of stresses which arise in adhesive joint at a given time section \( t_i \); \( \sigma_{[\tau_1]} \) and \( \sigma_{[\tau_2]} \) are standard deviations of acceptable values of actual stresses; \( \Phi \{...\} \) is a function of standard distribution.13

Taking into account the fact that processes of thermal destruction and loss of heat resistance take place simultaneously, they can be represented in the form of parallel connection, whose probability of failure-free operation \( P_{1,2}(t_i) \) is determined from dependence:
\[
P_{1,2}(t_i) = 1 - (1 - P_1(t_i))(1 - P_2(t_i)).
\] (28)

Taking into account that \( P_1 < P_2 \), dependence (28) takes the form of
\[
P_{1,2}(t_i) = P_1P_2 + (P_1 - P_1P_2).
\] (29)

Example of calculation of failure-free operation probability \( P_{1,2} \) for polyurethane adhesive is presented in Table 4.

| Temperature range, °C | \( \tau_1 \), MPA | \( \tau_2 \), MPA | Probability of failure-free operation |
|-----------------------|----------------|----------------|--------------------------------------|
| 20                    | 20             | 20             | 0.999                                |
| 100                   | 20             | 20             | 0.999                                |
| 200                   | 20             | 9.5            | 0.999                                |
| 300                   | 20             | 8              | 0.987                                |
| 400                   | 17             | 7              | 0.965                                |
| 500                   | 10             | 4              | 0.945                                |

The values of average breaking shear stresses by condition of heat resistance reduction \( \tau_j \) are determined by standard method according to GOST 14759. Average breaking stress values by condition of thermal destruction was found by thermal gravimetric analysis, conditionally assuming, that strength reduction will be proportional to mass loss at respective temperature values. For simplicity of performing calculations it was assumed that values of standard deviations by conditions of loss of heat resistance and thermal destruction are equal.

Assessment of failure-free operation probability of adhesive joint obtained on the basis of formula (29) is substantially reduced, because it does not take into account strength of correlation between two simultaneously proceeding processes.

Count of correlation between stresses \( \tau_j \) and \( \tau_j \) must be carried out in each moment of time, because they are determined by one and the same temperature impact. Simultaneously relationships between acceptable at a time corresponding values of bearing capacity \( \{\tau_j\} \) and \( \{\tau_j\} \), which may not be functions of time, should be taken into account.

Count of correlation on assessment of probability of failure-free operation of connection requires fulfillment of the following conditions: \( \tau_j \leq \{\tau_j\} \) and \( \tau_j \leq \{\tau_j\} \); random stress values are normally distributed for all time sections with average values of \( \tau_j \) and \( \tau_j \); their standard deviations \( \sigma_{[\tau_1]} \) and \( \sigma_{[\tau_2]} \) can have a constant value for any time sections in a linear uniform law of degradation. Count of correlation relationships allows introducing correcting factor \( K \).

Having assessment of probability (26) and (27) as well as characteristic of correcting factor \( K \), we can determine the probability of failure-free operation of adhesive joint by formula:
\[
P_{1,2}(t_i) = P_1P_2 + (P_1 - P_1P_2)K.
\] (30)

4. Discussion

This article explores adhesive joint of carbon fiber composite tube and metal bushing by means of a polyurethane adhesive VK-20 modified by carborane compounds. Investigations were conducted on exposure to temperatures of -120°C and +150°C.
5. Conclusion

In result of studies of spatial composite structures of rocket and space techniques the following conclusions were stated:

- Calculations of stress-strain state of adhesive joint were conducted, upon completion of which shear and breaking stresses in the contact area between the bonding parts were defined;
- According to results of calculations of stress-strain state of adhesive joint, studies were conducted aimed at definition of analytical dependences, allowing describing the behavior of adhesive joint exposed to elevated temperatures. The whole area of adhesive operating temperature is divided into two ranges. In the first range there are processes of gradual reduction of heat resistance which is driven by destruction of adhesive joint. In the second range processes of thermal destruction take place which are driven by cohesive destruction of adhesive material. Starting from some temperature (for the given adhesive VK-20 it is the range of from 400 to 800°C) strength reduction is influenced by both processes. The proposed equation allows estimating the probability of failure-free operation of adhesive joint, including consideration of correlation coefficient.
- Conducted calculations have shown that heat-resistant polyurethane adhesive VK-20, modified by carborane compounds provides reliable operation of adhesive joint: the probability of failure-free operation is not lower than 0.945.

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7. References

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