Experimental and numerical studies of the design of statically indeterminate turbojet engines

Eksperymentalne i numeryczne badania konstrukcji statycznie niewyznaczalnych silników turboodrzutowych

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The article presents a methodology for designing an aircraft frame with a maximum take-off weight of up to 5700 kg. The study was based on a model of a turbojet engine truss intended for use in aircraft of this category. The objective was to develop a design approach using commercially available tools for the design, construction, and manufacturing of such structures.. The resulting truss structure is designed to withstand a range of internal and external loads, including thermal displacements and deformations.
KEYWORDS: truss design, lattice structures, frame structures, FEM

Artykuł przedstawia metodykę projektowania ramy samolotu o maksymalnej masie startowej do 5700 kg. Badania oparto na modelu kratownicy silnika turboodrzutowego przeznaczonego do zastosowania w samolotach tej klasy. Celem było opracowanie podejścia projektowego z wykorzystaniem ogólnodostępnych narzędzi do projektowania, konstruowania i wytwarzania tego typu struktur. Powstała konstrukcja kratownicowa została zaprojektowana tak, aby wytrzymywać zakres obciążeń wewnętrznych i zewnętrznych, w tym przemieszczenia i odkształcenia cieplne.
SŁOWA KLUCZOWE: projektowanie kratownic, konstrukcje kratowe, konstrukcje ramowe, MES

Introduction

The purpose of the structure, its operational parameters, and the results of a potential failure are the basic factors that should be taken into account in aircraft structures. The weldability of the material used is a basic feature taken into account when selecting a material for the production of a truss. It is the primary determinant of the material's suitability for the structure in the joint creation phase. It should be kept in mind that the thermal welding process nearly always causes local deterioration of the key properties of the parent material and introduces residual stresses which can reduce the structure's reliability level. In order for the structure to meet the operational requirements, additional processes may be necessary to prevent material degradation before and after the welding process. Frames used in aircraft structures are heavily loaded structures with complex structural solutions resulting from the functions they fulfill. They are required to have high strength under static and variable loads, high stiffness, and also the possibility of shaping them in such a way that they are functional in their solution. When introducing structural solutions, the possibilities for their production and the use of technologies permitted in aircraft structures should be taken into account. The engine mounting frame is a truss-frame structure. It consists of steel fittings, to which the engine and front chassis are attached, and a system of steel pipes joined by welds. It was assumed that the frame would be made as a lattice structure, made of circular cross-section pipes with external diameters up to 24 mm and wall thicknesses t from 1.5 to 3 mm. The design assumes that the pipes are directly welded together to minimize the use of gusset plates, thereby reducing the structural weight. With such a solution concept, the construction required the use of connecting nodes containing 2 to 9 elements meeting in one node. The view of the lattice structure is shown in fig. 1. In each node of the bed, the main pipes are connected by welds through special nodal pads, then the remaining pipes meeting in a given node are welded to them. The nodal pad is 2.5 mm thick and has an outer diameter 1 mm smaller than the welded pipes, while its inner diameter is 10 mm. All structural elements are made of 1.7734.5 steel. The strength properties of 1.7734.5 steel are asfollows: Rm = 1180 MPa, Re = 1080 MPa, γ = 0.0085 kg/cm^2 based on catalogues and our own research (strength tests: uniaxial tensile test, tests at elevated temperature, burst and weld pull-out tests) Tab. 1. [1].

Strength calculations of bed pipes

The engine bed is a truss-frame structure made of steel pipes with high mechanical strength. Strength calculations were performed for all important strength elements of the truss structure using two calculation models based on the FEM (finite element method).

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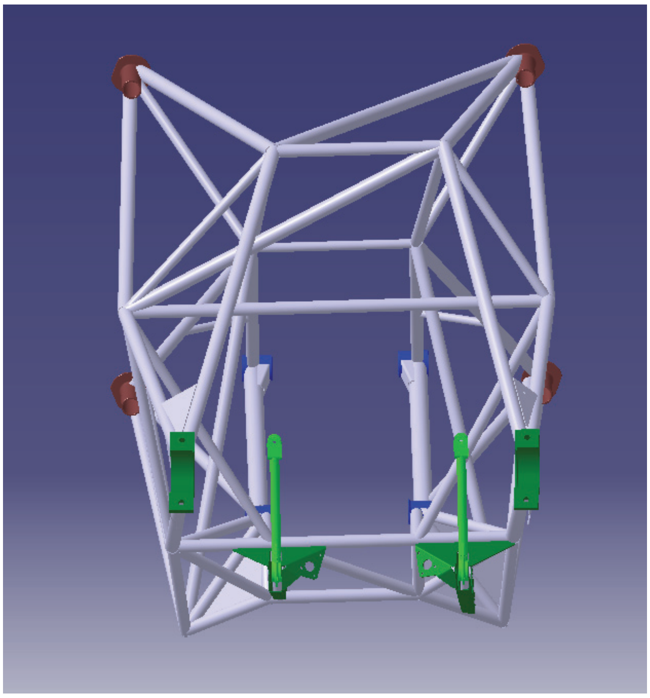

Fig.1. Front view of the frame with mounting nodes
Rys.1.Widok z przodu na węzły mocowania ramy silnika

The first model is a model with a simplified beam model of the engine suspension, with a propeller and the front landing gear suspended on the engine mount nodes. The second model is a precise model of the truss structure modeled using TETRA-type finite elements.

Table I. Mechanical properties of the material
Tabela I. Mechaniczne właściwości materiału

Material	Steel
Young's module	2e+011 N/m^2
Poisson's ratio	0,3
Density	7860 kg/m^3
Coefficient of thermal expansion	1,17e-005/Kdeg
Yield strength	1,0e+009 N/m^2
Ultimate strength	1.15+009 N/m^2

External loads of the bed originating from the engine, propeller, and nose gear were performed according to our own documentation for 17 load cases (12 in flight and 5 on the ground). These loads were applied to the nodes of the first model, reflecting the position of the propeller, the center of gravity of the engine with the bed and the center of gravity of the retracted nose gear for cases in flight and at the wheel axis or at the point of contact between the tire and the ground for cases on the ground. The FEM module of the CATIA program (Analysis & Simulation module) was used for calculations. For the first model, the forces acting on the engine and nose gear suspension nodes were obtained, which were applied to the nodes of the second bed model. After analyzing the determined forces, 5 load cases in flight and 2 load cases on the ground were selected for further calculations. As a result of calculations with the CATIA program (Analysis & Simulation module) of the second model, stress distributions were obtained for all elements of the bed for the selected load cases. Model 1 is a simplified beam representation of the engine suspension with the propeller and the front landing gear. These models are suspended on the engine bed nodes. The models are built from beam elements with high stiffness and are used only to determine the loads of the engine suspension fittings and the front landing gear. In the calculations carried out in the Catia program (Analysis & Simulation module), in order to determine the forces in the contact elements of the models with the bed fittings, eight sensors were utilized 4 for the engine connection and 4 for the landing gear connection. The results of the pre-selected load cases are in the table below. The highest Von Mises stresses occur in the case of GIRO A loads; in one of the most loaded elements they are 521 MPa and for this pipe the safety margin is:

$$\mathrm{MS} = \frac{Rm}{\sigma \cdot f_c} - 1 \tag{1}$$

where:
Rm = 1180 MPa – material strength of a given element,
σ = 521 MPa – maximum stress in a given element,
f_c = 1.5 – safety factor according to CS23.303

$$\mathrm{MS} = \frac{1180}{521 \cdot 1.5} - 1 = 1.51 - 1 = 0.51 \tag{2}$$

The safety margin is greater than 0, so the strength of the pipe is sufficient. If < Re then there will be no permanent deformations in the element 521 MPa < 1080 MPa there will be no permanentc deformations in the pipe [2, 3].

Static test object

Static tests were carried out on the engine bed truss, made in accordance with the design specification. The bed truss was attached to the stand at 4 nodes designed for attaching the bed to the aircraft fuselage frame and loaded using special loading systems

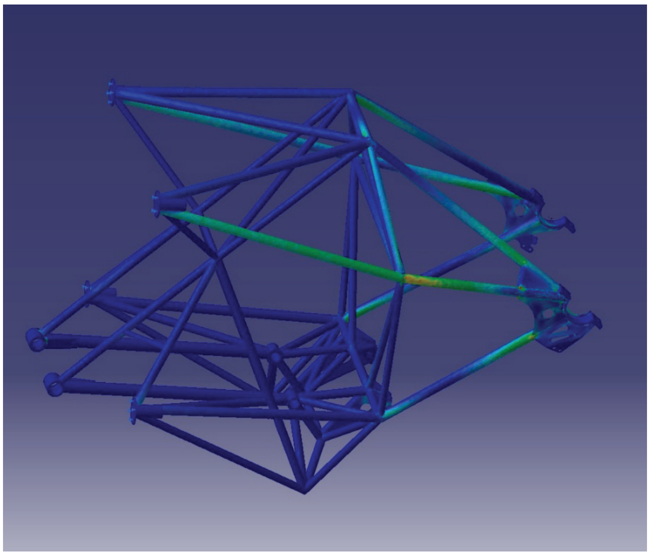

Fig. 2. Stress distribution in the engine frame elements under the influence of forces resulting from the load envelope.
Rys. 2. Rozkład naprężeń w elementach ramy silnika pod wpływem sił wynikających z obwiedni obciążeń

Table II. Maximum stress values obtained during tests for measuring points
Tabela II. Maksymalne wartości naprężeń uzyskane podczas badań punktów pomiarowych

Test	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12
	MPa											
OBC X Load	−19	−32	−8	−20	−43	75	109	−55	−47	−105	−132	−21
DOB H Load	33	−64	−11	−35	132	129	205	47	10	6	−5	13
TORQUE 1 Load	−109	412	147	104	97	−271	119	147	−3	−3	−13	5
Girona's Burden	−78	354	129	80	−75	−317	−60	−311	−1	−4	−12	4
Giro A Load to Destruction	192	564	348	−104	108	−574	−179	−441	2	−8	−21	7

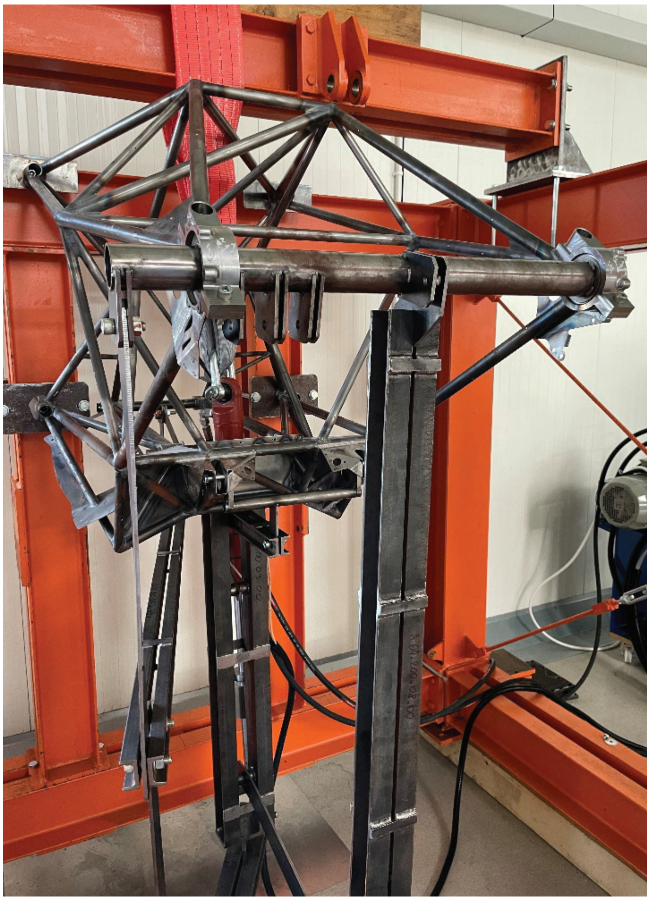

Fig. 3. Engine bed truss mounted on static test stand with marked measurement points
Rys. 3. Kratownica łoża silnika zamontowana na stanowisko do prób statycznych z zaznaczonymi punktami pomiarowymi

(different in each load case) with two actuators (fig. 3). Static tests were performed in accordance with the design specifications to verify structural strength under operational and extreme load cases. The truss was mounted to a static test stand at four attachment nodes, which are designed for its attachment (simulation of attachment to the aircraft frame). The truss should be equipped with elements corresponding to the engine and front landing gear attachment, enabling correct introduction of loads provided for in the program. In the places selected on the bed truss, strain gauges should be glued to measure and control the applied loads and stresses in the critical areas of the truss (table II). Indicators for measuring displacements under the influence of loads should be mounted in the front engine mounting nodes.

Cases 1 and 2 characterize the highest frame loads on the ground, while cases 3 and 4 characterize the engine bed load cases in flight. Static tests of the aircraft engine bed truss were carried out for 4 load cases dimensioning up to 150% of the operating loads. For the load case dimensioning the strength of the bed truss (GIRO A), the 5th test will be carried out was carried out to destroy the bed truss structure. The purpose of the static tests of the engine bed truss is to check the static strength of the engine bed structure and the mounting nodes. The test program presents the requirements for applying and controlling loads in during the tests and conducting stress and displacement measurements in individual tests (fig. 4, 5) [4, 7].

The tests were developed and conducted in order to determine the actual displacement courses in the front engine mounting points and stresses in selected bed truss tubes, where the highest stresses were expected, and to compare them with the results of numerical calculations.

5 static tests were carried out for the following load cases:

- OBC X load case up to 100% and 150% of loads
- DOB H load case up to 100% and 150% of loads
- TORQUE 1 load case up to 100% and 150% of loads
- GIRO A load case up to 100% and 150% of loads
- GIRO A load case up to truss destruction (230% load and maximum force in the actuator reached) [5, 6]

Conclusions

In all tests up to 150% of the allowable loads, the strain gauges worked linearly, which means that the stresses in the measured pipes did not reach the yield point, so there were no permanent deformations in the truss. In the test to destruction, the engine bed

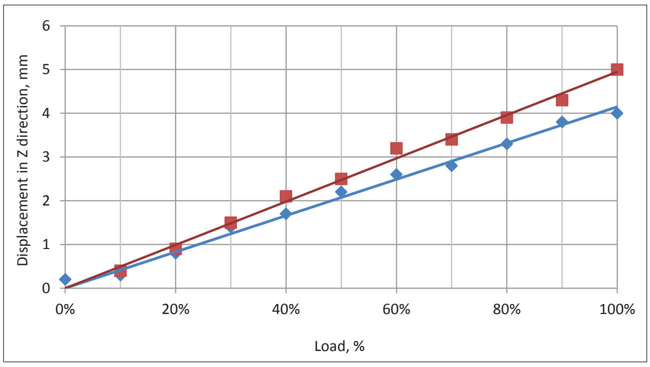

Fig. 4. Displacement values for a given structure load
Rys. 4. Wartości przemieszczeń dla danego obciążenia konstrukcji

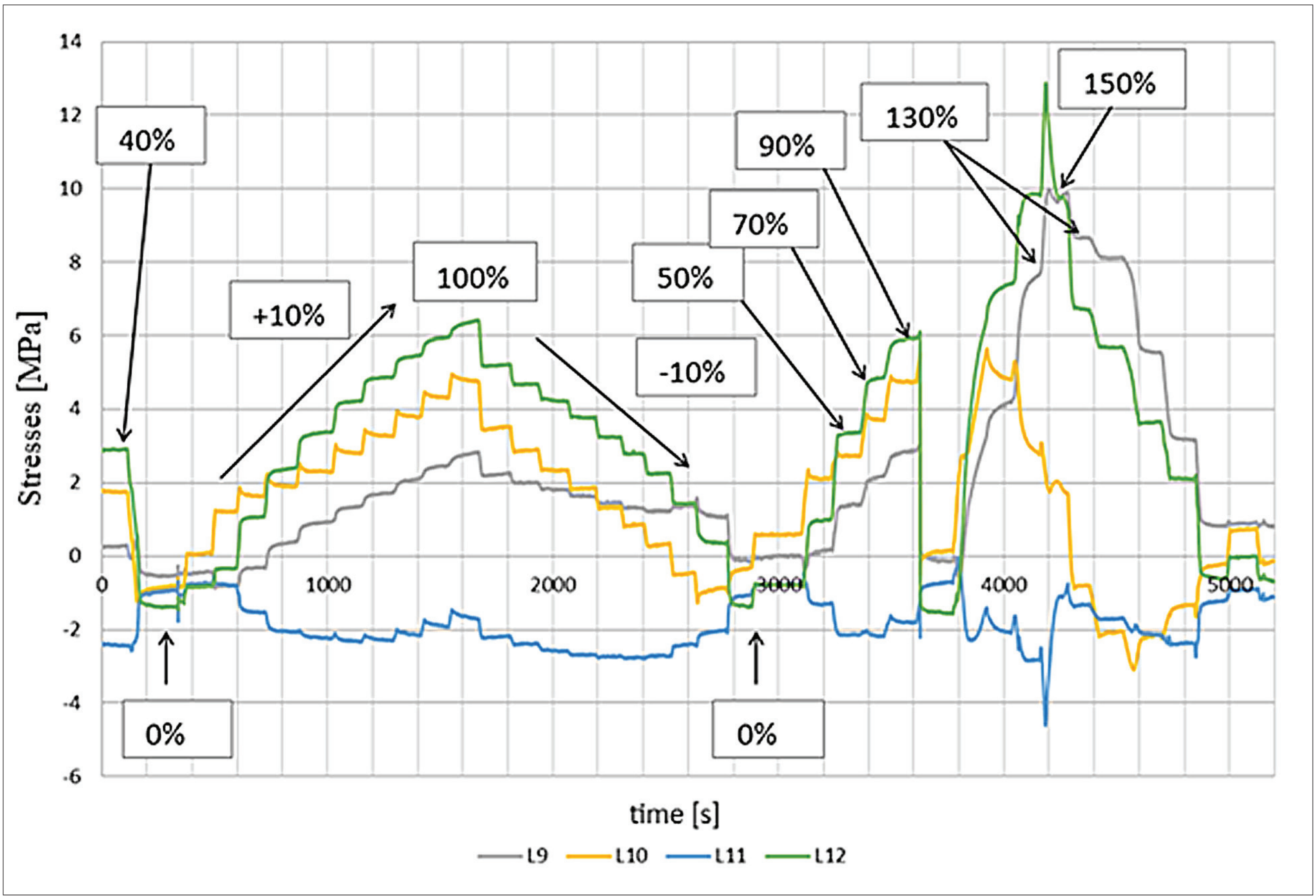

Fig. 5. Stresses recorded by strain gauges L9-L12 and percentage of load (Load case DOB H)
Rys. 5. Naprężenia zarejestrowane przez tensometry L9-L12 oraz procentowa wartość obciążenia (Przypadek obciążeń DOB H)

truss was not damaged, due to the maximum allowable pressure being reached in cylinder no. 2; the test was stopped when the load reached 230%. The maximum stress curves at the maximum load show nonlinearity, but after removing the loads, the stresses returned to zero, so there were no permanent deformations of the truss. The disproportionate increase in stresses from the loads was caused by a change in the nature of the loads associated with significant deformation of the structure. The tests yielded greater displacements than the results obtained from theoretical calculations, which results from the method of attaching the truss to the cage beams. The truss supports are deformable objects, while in the calculations the truss supports are assumed to be infinitely stiff. The stresses measured in the static tests are normal stresses acting along the axis of the truss tubes, while the stresses determined by calculation in the same tubes are reduced stresses determined according to the von Mises hypothesis. Normal stresses should be lower than reduced stresses and, with in this analysis, this regularity is maintained. The stresses measured in the tests and determined in the calculations are at the same level, so the results of the static tests confirmed the correctness of the strength calculations. The static tests showed sufficient static strength of the engine bed truss. Achieving 230% of the loads for the most dangerous load case from the strength perspective provides a safe margin for the development of the aircraft with a bed for this engine.

Acknowledgments

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