Critical strength cases for particular components of gliders

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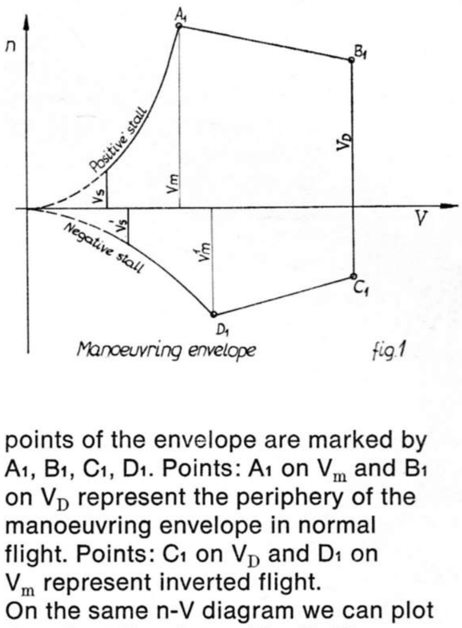
1. Introduction

To perform the preliminary design of a glider it is necessary to know the strength limiting loadings for particular components. The full technical documentation requires, of course, very detailed calculations of the loads but in the very beginning of the work it would be profitable to know which load cases have the deciding influence in establishing the safety factors for the various components of the glider. In other words the signs of all structural members depend on the greatest values of load which may occur in the various cases. The main question now is which load is the governing one for the component considered. The answer to the above question is given by experience. The observations and experience gained by designers when calculating the loads permit the elimination of many loading cases and hence the determination of the critical strength cases only.
The aim of the present paper is to approach the problem of establishing the main load cases, the application of which can give a general picture of the strength properties of the design under consideration. It is well known that the value and character of the loads depend on the national design requirements. Because of this it is recommended that the investigation is made on the basis of international OSTIV requirements. Here, however, a difficulty arises. The statistical data for designs based on OSTIV requirements are at present very limited. All the existing gliders are designed in order to obtain national Certificates of Airworthiness and so are built according to national requirements.
The considerations of the present paper are based on the Polish Design Requirements, for two reasons:
– The Polish Requirements as regards loads are very close to the OSTIV requirements.
– Quite a wide range of statistical data applicable to Polish designs was accesible to the author, allowing some generalized conclusions to be drawn.

2. Nature of the loads

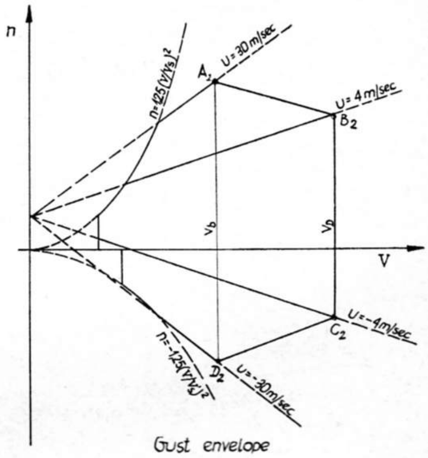
For load calculation purpose the glider is assumed to be a rigid body. It is subjected to the action of both external and internal systems of forces. The external forces are represented by aerodynamic load, the forces of the tow rope, the reactions of shock absorbing elements etc.
The internal system consists of inertia forces, being the responses of the glider to all the linear and rotational accelerations involved as a consequence of the action of the external forces. Both internal and external systems are in equilibrium considering the glider as a whole.
The loads, in respect of their character, can be divided into two groups:
– Flight loads.
– Ground loads.
Flight loads appear as reactions of the glider to pilot's manoeuvres, to gusts, or to tow rope pull.
The manoeuvre loads arising as a consequence of deflections of controls are expressed graphically by n-V diagramm (the so-called «Manoeuvring Envelope»), where «n» is the manoeuvring load factor and «V» is the speed of flight EAS (fig. 1). The main



Manoeuvring envelope fig.1

points of the envelope are marked by A_1, B_1, C_1, D_1. Points: A_1 on V_m and B_1 on V_D represent the periphery of the manoeuvring envelope in normal flight. Points: C_1 on V_D and D_1 on V_m represent inverted flight.
On the same n-V diagram we can plot the «Gust Envelope» (fig. 2). The straight lines beginning at $n=1$ represent the gusts of intensity 30 and 4 m/sec in up and down directions. The periphery of the gust envelope is marked by points: A_2 on V_b and B_2 on V_D for up-gusts and C_2 on V_D and D_2 on V_b for down-gusts.

Superimposing these two diagrams (for manoeuvring and gust loadings) on one coordinate system n-V we obtain the general envelope of normal accelerations in flight. Its periphery we mark by points A, B, C, D. Therefore the point A is either A_1 or A_2 whichever has the greater value of «n» factor. The same philosophe applies to the points B, C and D. The effect on the glider of manoeuvring or gust loads is from the static point of



Gust envelope fig.2

view the same, and this is the reason of introducing a single overall envelope.
The tow rope loads act in various directions. In calculations we take into account only the most extreme directions of the rope upwards, downwards and sideways.
Ground loads are those which may occur during launching, landing, taxying and ground handling. Assuming that in cross-country flight landings on ordinary fields (mainly the larger fields of corn, meadows etc.) the ground handling is carried on by inexperienced people, the different components and elements of the glider are subjected to various unexpected loads. The values of these are determined from the requirements. The loads arising during launching, landing and taxying are connected with the character of the shock absorbing elements or, in the case of a fixed wheel, with the ability to absorb the shock energy by the structure as a whole.
All the above-mentioned loads act on particular components of the glider, producing stresses in the structure.
In the next sections there will be examined the loads on wing, aileron, flap, fuselage and tail unit in an attempt to select the governing cases. This is to aid the designer in performing the preliminary structural analysis of a new prototype concept.

3. Wing

The character of the loads on the wing is expressed by means of bending and twisting moments accompanied by shear forces. On the diagrams their values are plotted against fraction of wing semispan. To define the external system of forces it is necessary to calculate the lift distribution along the wing span. This distribution depends on the combination of the shape of the wing planform and aerofoil section chosen by the designer. The internal forces system depends on the mass distribution along the wing span. In common practice this distribution is assumed to be proportional to wing chord. The full loading system is given on fig. 3.

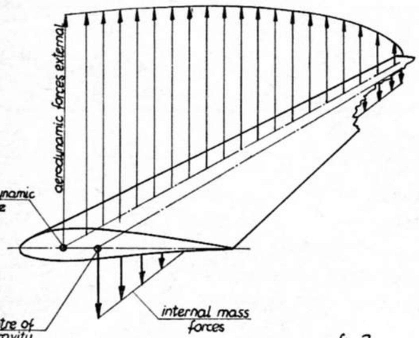


fig.3

The diagrams of wing bending moment in the most severe cases for several gliders are shown in figs. 4—10, in which the numbers on the curves denote the following loading cases:

1. Point A of envelope.
2. Point D of envelope.
3. Point C of envelope.
4. Sharp up-deflection of aileron.
5. Sharp down-deflection of aileron.
6. Inexperienced ground handling.
7. Heavy landing.

Positive values of bending moment are taken for upwards bending and negative values for downwards bending. For all the example gliders, the limiting positive bending take place for point A of the envelope and negative bending for point D. This is true for the semispan range from y/(b/2) = 0 to y/(b/2) = 0.65 to 0.7. For the semispan range from y/(b/2) = 0.65 to 0.7 to y/(b/2) = 1.0 the most severe condition is the case of inexperienced ground handling. It ist easy to see that the other cases plotted on the diagrams, or others not mentioned, like points B and C of the envelope, heavy landing, steady roll etc. can be omitted in preliminary strength calculations for the prototype wing.

When in the design there is used an anisotropic material, like e.g. metal, a further simplification can be made. In this case only the bending moment for point A of the envelope is critical. Using an orthotropic material, like e.g. wood, this simplification applies provided that the ratio of ultimate

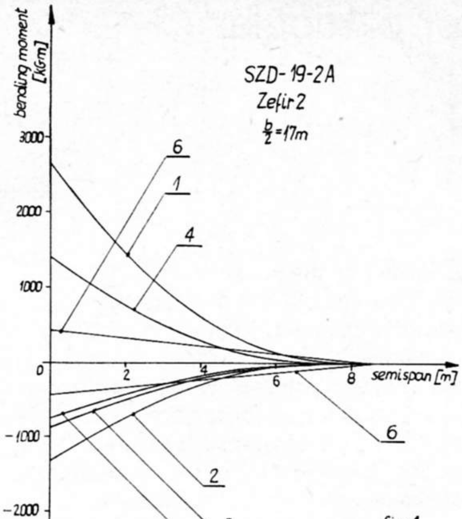


fig.4

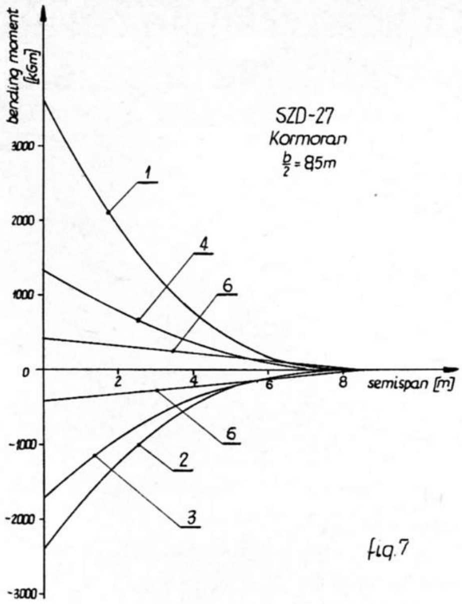


fig.7

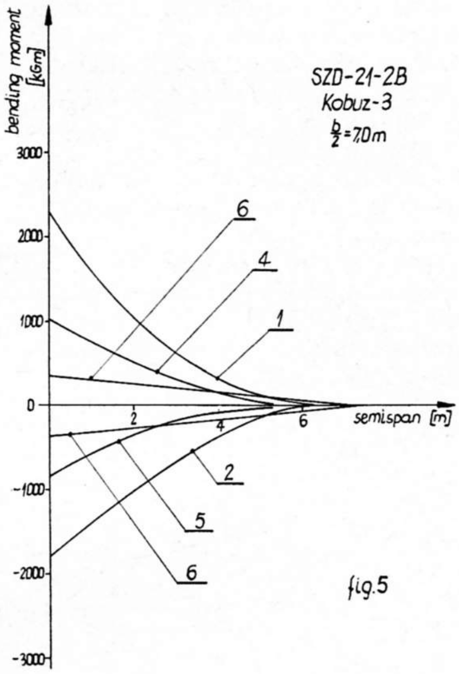


fig.5

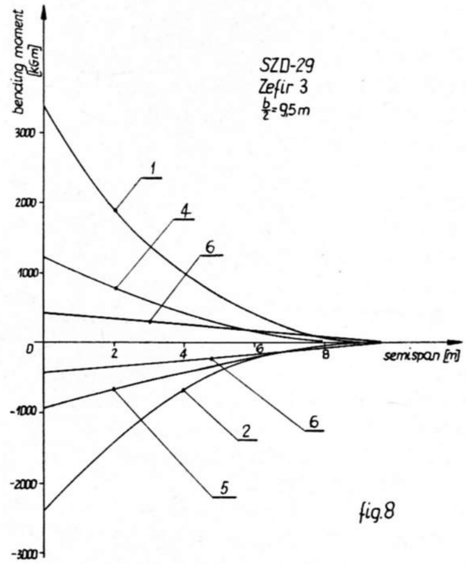


fig.8

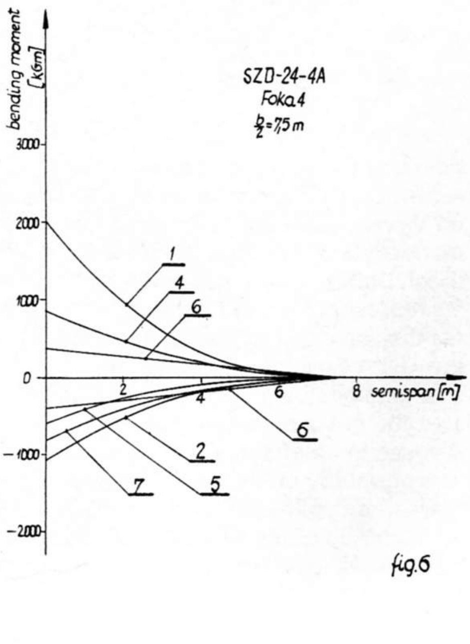


fig.6

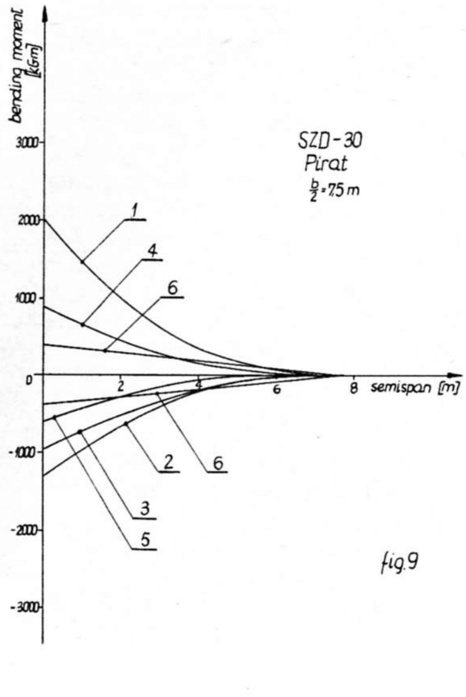


fig.9

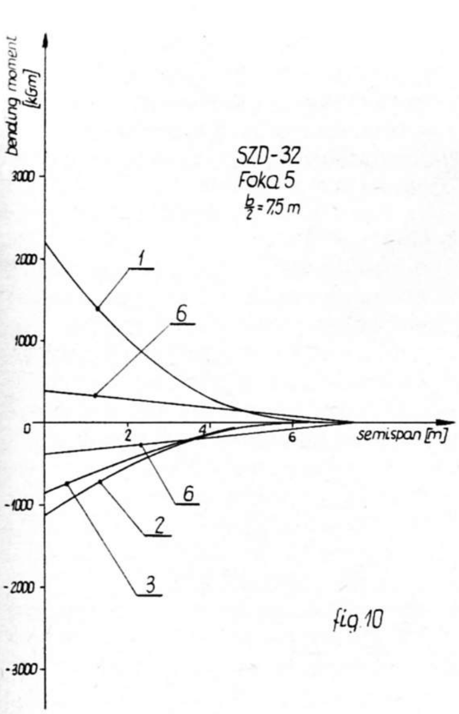


fig. 10

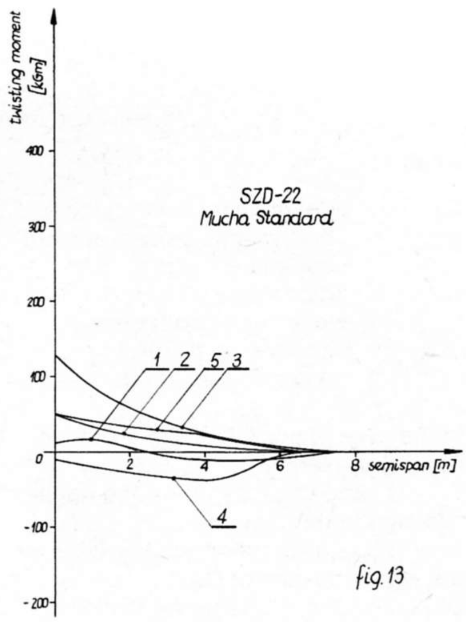


fig. 13

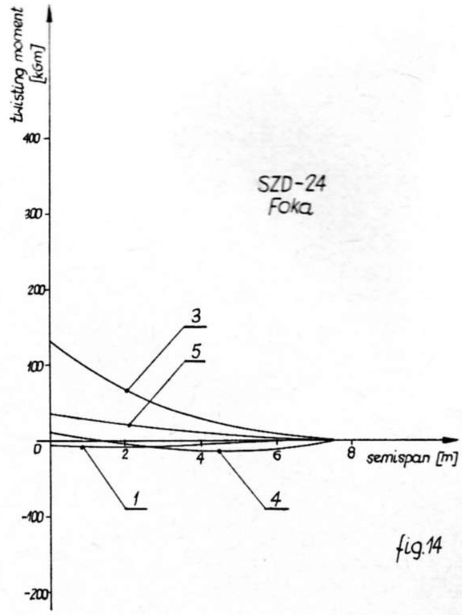


fig. 14

strengths and bending moments fulfil the formula:

$$\frac{R_c}{R_t} \geqslant \frac{M_D}{M_A}$$

where:

R_c — ultimate strength of wood in compression
R_t — ultimate strength of wood in tension
M_A — bending moment for point A of envelope
M_D — bending moment for point D of envelope

Loads given here as examples were calculated for the wing treated as a stiff body. This assumption is true for the wing of average torsional stiffness and for speeds of flight up to 250 km/h (approximately). For wings of comparatively low torsional stiffness or for diving speed $V_D > 250$ km/h it is possible that the bending moment for point C of the envelope for the elastically deformed (twisted) wing can be the critical case for downwards bending. On figs. 11—17 there are presented the twisting moments for several example gliders. The general conclusion is that the most severe case for torsion appears to the point C of the envelope. It becomes quite clear when we remember that almost all normal gliders employ aerofoils having the positive aerodynamic centre moment coefficient $C_{m\ a.c.}$, assuming the nose down direction as positive. (Note that this is the opposite sign convention to that used in many countries — Editor.) In the case of point C of the envelope the lift is directed downward. The flexural axis lies in most cases behind the aerodynamic centre (mesured along the chord from nose). Moreover the section centre of gravity lies behind the flexural axis when the inertia forces are being directed upwards. In such a

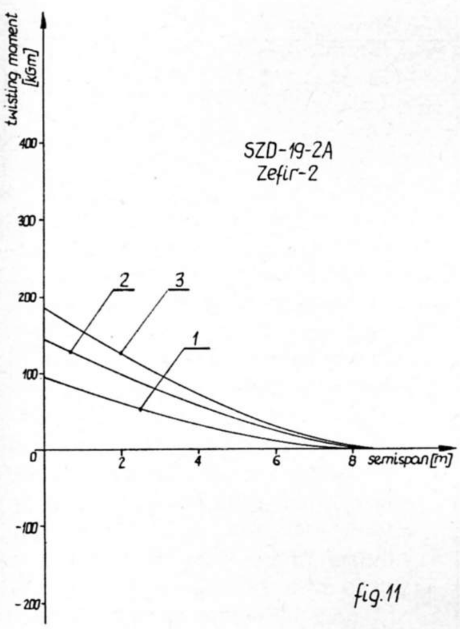


fig. 11

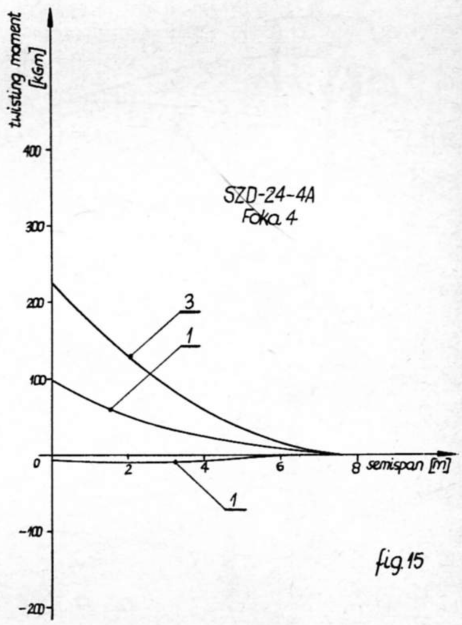


fig. 15

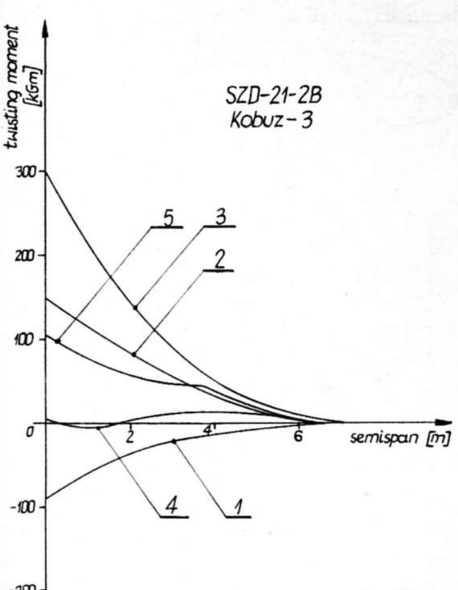


fig. 12

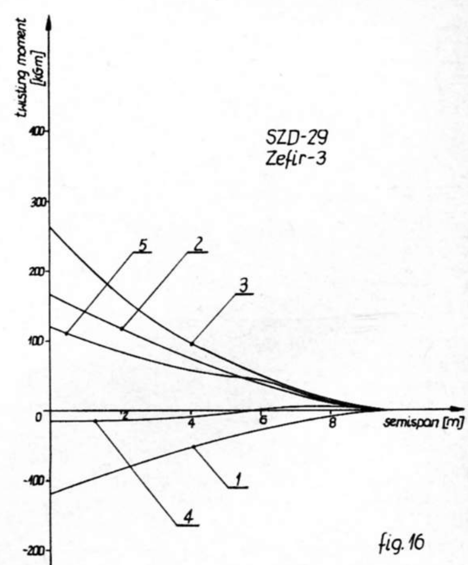


fig. 16

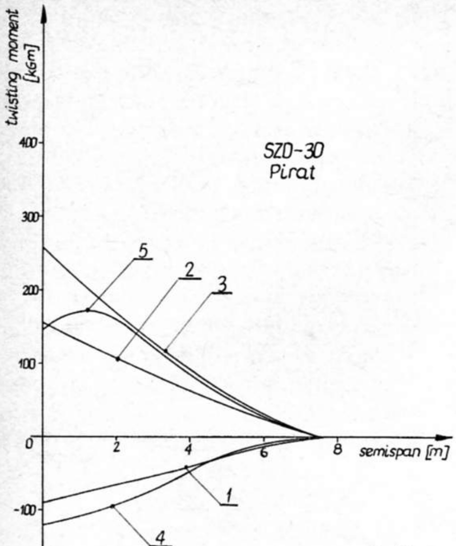


fig.17

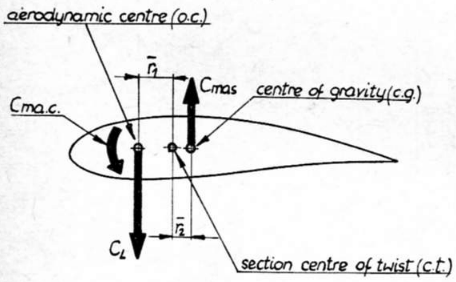


fig.18

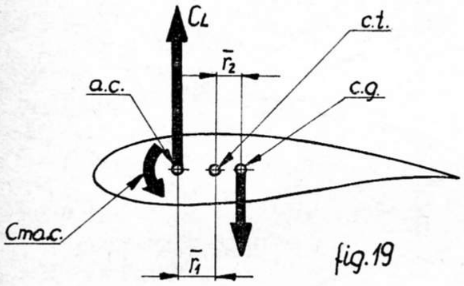


fig.19

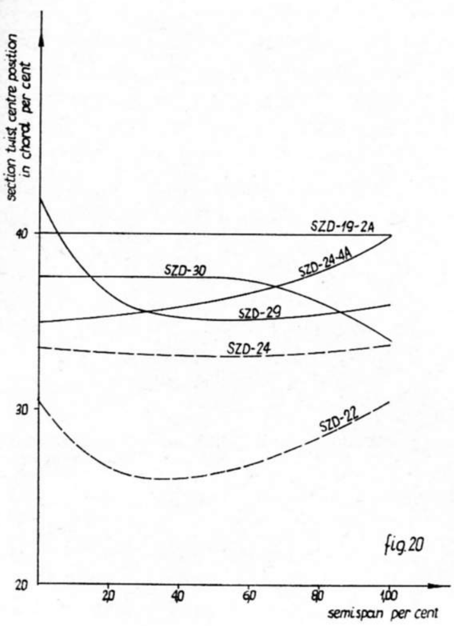


fig.20

case (fig. 18) the moment coefficient consists of the sum of the expressions:

$$C_m = C_{m\,a.c.} + C_L \times \overline{r}_1 + C_{mas} \times \overline{r}_2$$

where:

C_m = total moment coefficient
$C_{m\,a.c.}$ = aerodynamic centre moment coefficient
C_L = lift coefficient
C_{mas} = mass force coeffecient
$\overline{r}_1, \overline{r}_2$ = distances to flexural axis related to the chord.

In the case of point A of the envelope (fig. 19) the terms:
$C_L \times \overline{r}_1$ and $C_{mas} \times \overline{r}_2$ have the opposite sign to the term $C_{m\,a.c.}$ giving a rather law value for the algebraic sum of C_m.
Observing the diagrams we come to the conclusion that the gliders having single-spar wings (SZD–22 Mucha Standard, SZD–24 Foka) show rather low values of twisting moment at point C of the envelope, when compared with gliders having monocoque or multi-spar wings (the rest of the example gliders). This depends on the chordwise position of section twist centre. For single-spar wings the section twist centre lies farther forward in the wing than for monocoque or multi-spar wings (fig. 20).
In most gliders the twisting moment of the wing is carried by a torsion box stressed independently of the moment direction (upwards or downwards). Therefore the twisting moment of point C of the envelope becomes the limiting strength case for establishing the skin thickness.

4. AILERON

The aileron leading results from pressure distribution along the chord of that part of the wing which embodies the aileron. The shape of this distribution is assumed according to the linearized method (fig. 21). The triangular form of distribution on the aileron with maximum pressure value of 2p gives the mean pressure of p. The recommendations for load calculations require that the full up and down deflection of the aileron at speed V_m is accompanied by pull up to points E'_1, and E''_1 of the envelope with load factors $n_{E'1}$ = 1/2 n_{A1} and $n_{E''1}$ = 1/2 n_{D1} respectively (fig. 22). The results of calculations for several of example gliders are gathered in table I where the down deflation (β^+) is assumed as a positive pressure and uf deflection (β^-) as a negative one. The strength limiting value of the loading appears for full down deflection of the aileron in normal flight or with full up deflection in inverted flight. In most cases however the former gives the greater load value.

Since the pressure distribution is always triangular, the maximum pressure case is the strength limiting one for both bending and torsion independent of the section twist centre position.

5. Flap

The loading of a lift flap is to be found in the same way as for an aileron. The problem is however simplified because the flap is used only in normal flight that means only in the positive part of the envelope (fig. 23). The diagram shows that maximum bending

Tab. I

			mean aileron pressure p [kG/m²]			
			$n = \frac{1}{2} n_{A1}$		$n = \frac{1}{2} n_{D1}$	
	β^+	β^-	β^+	β^-	β^+	β^-
SZD-19-2 Zefir-2	15°	-30°	61,2	-47,2	46,4	-65,4
SZD-21-2B Kobuz-3	15°	-30°	113,7	-62,4	75,5	-100,5
SZD-24-4A Foka-4	15°	-34°	102,6	-82,6	55,2	-80,2
SZD-27 Kormoran	15°	-30°	60,5	-89,6	68,5	-112,5
SZD-29 Zefir-3	10°	-25°	90,5	-69,8	78,2	-81,9
SZD-30 Pirat	15°	-30°	82,7	-65,3	70,0	-78,0
SZD-32 Foka-5	15°	-35°	101,5	-63,5	77,6	-85,5

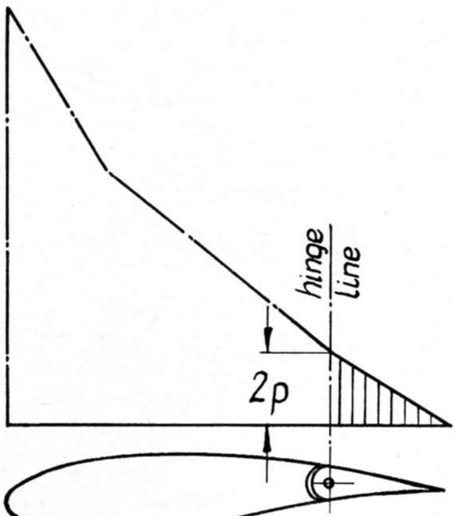


fig.21

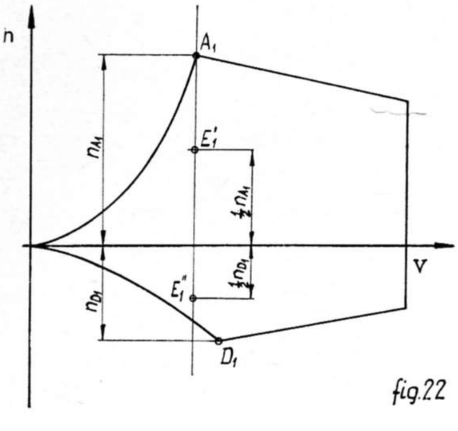


fig.22

and torsion occur in the case described by point F_2 because at that point the maximum of load factor n_{F2} is combined with the maximum dynamic pressure, obtained at speed V_F (in the range of speeds permissible for flight with flaps extended).

6. Fuselage

The fuselage is subjected to various kinds of load. Load in flight as a consequence of pull-out manoeuvres or gusts are defined by points A, B, C, D of envelope's periphery. In this case the fuselage, treated as a beam supported on the main wing fittings, is loaded by external aerodynamic force acting on the horizontal tail and by a system of inertia forces distributed along the fuselage longitudinal axis proportional to the mass distribution (fig. 24). There is no rotation of the fuselage, so the inertia forces are produced only by the linear accelerations. All the above forces are in equilibrium with the reactions appearing on the main wing fittings.

In case of tow rope loads we observe another shape of load distribution. The external forces on the horizontal tail and on the towing hook produce linear accelerations. Since the point of application of the tow rope force lies at some distance L from the c.g. of the glider it produces rotation of the fuselage around the c.g. This motion involves rotational acceleration. In consequence there exists a complex acceleration system producing a similarly complex system of inertia forces. All the external and internal forces are in equilibrium (fig. 25).

In the case of load produced by sharp deflection of the elevator the system of external and internal forces and moments is the same as described above for tow rope loading, with the exception that the load producing rotation is applied at the tail.

The above discussed cases of loads in flight are referred to the vertical plane. The same effect take place in the horizontal plane if there exists a horizontal gust or sharp deflection of the rudder or a sideways pull of the tow rope.

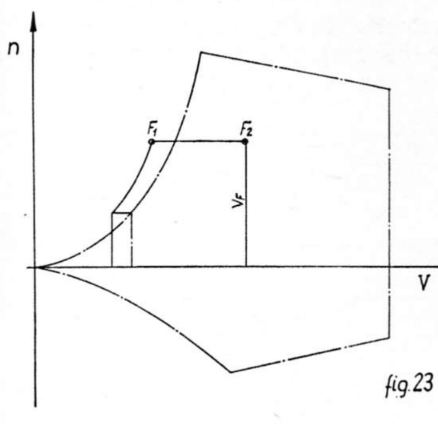


fig.23

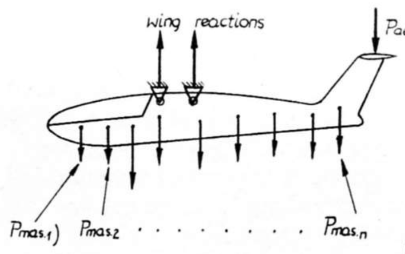


fig.24

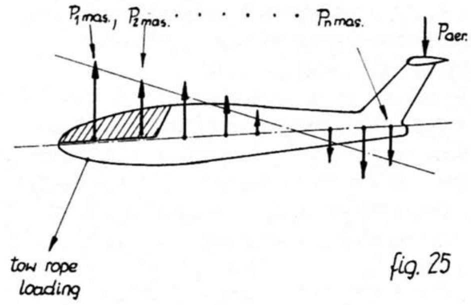


fig. 25

The ground loads arise mainly during heavy or touch landing. (Editor's Note – «Touch landing» is the literal English translation of the original Polish expression. The nearest English term is probably «nose down landing», but the touch landing includes also the case of the glider running into an obstruction such as a molehill.) The value of the acceleration and consequently of the inertia force depends mainly on the shock-absorber reaction and the distance of its point of application from the c.g. of the glider. The cases of most severe loads of the fuselage for the example gliders are plotted on diagrams figs. 26–31, where the numbers denote the following cases:

1. Point A of envelope
2. Point D of envelope
3. Tow rope down-force
4. Tow rope up-force
5. Sharp deflection of elevator
6. Heavy landing
7. Touch landing

The shapes of the bending moments diagrams are rather complex (in the periphery region). The strength of the front part of the fuselage from the nose to about 25 per cent of the total length is governed by the tow rope load case. The middle part of the fuselage comprising the pilot's seat, main wing fittings and landing gear is critical for points A and D of the envelope. The rear part of the fuselage (from the rear wing fitting to the tail) has several variations of strength-limiting cases. When the glider is of vertically symmetrical fuselage cross section (that is, as regards longeron cross sections and distances from the main geometrical axis, plywood thickness etc.) the limiting case is downwards bending caused by the sharp deflection of the elevator. For asymmetrical cross sections the

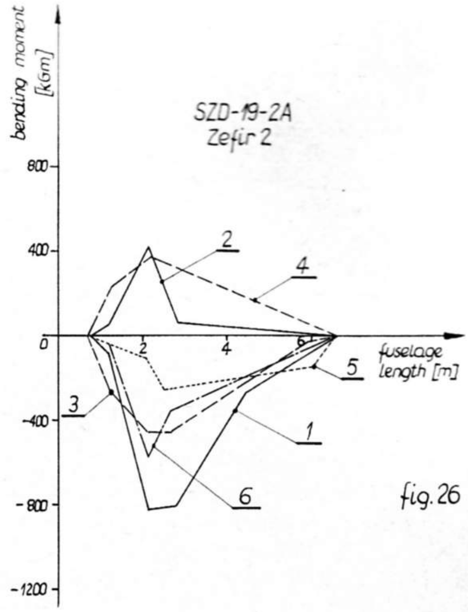


fig.26

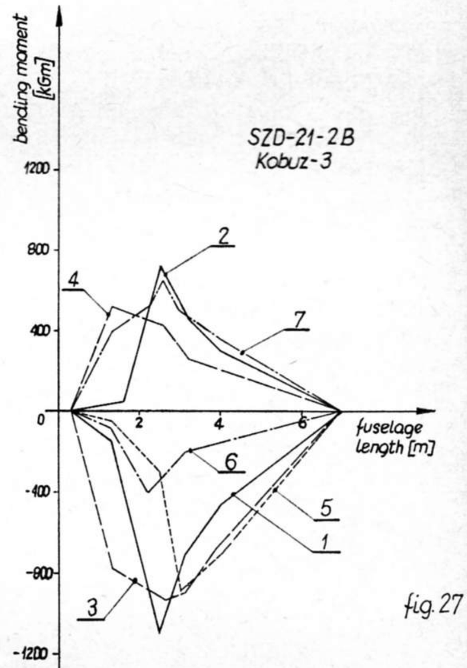


fig.27

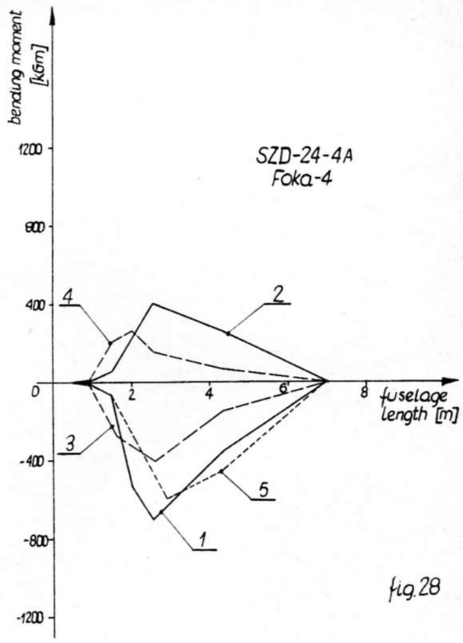


fig.28

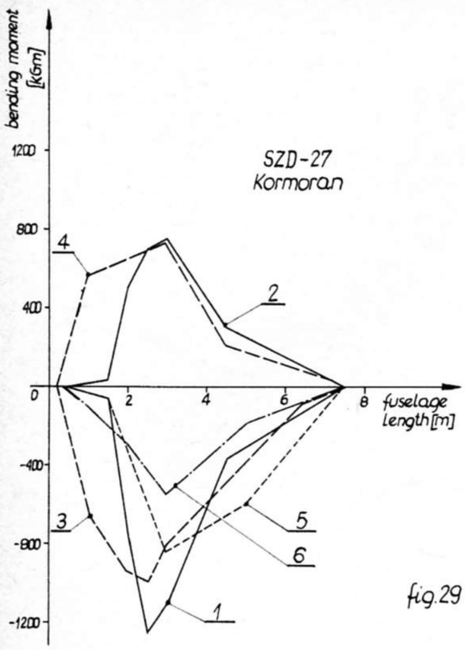


fig.29

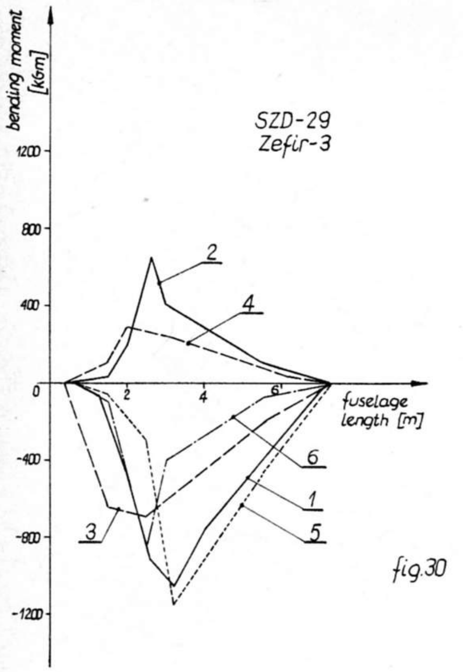


fig.30

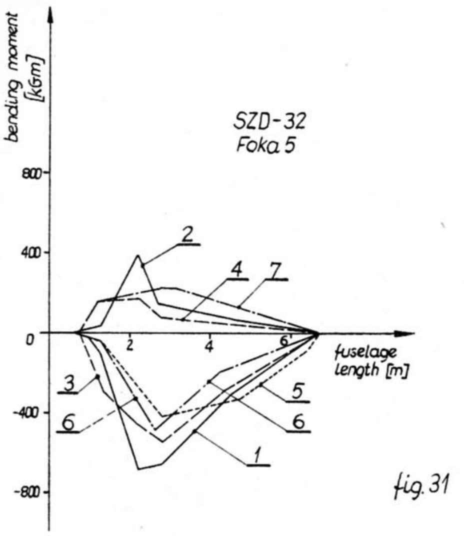


fig.31

up-bending is limited by either point D of the envelope or by the touch landing case.

The diagrams of bending moment acting in the horizontal plane are rather simple and are therefore not presented here. Analysis of them shows that for the front part of the fuselage the limiting case is tow rope sideways pull. For the rear part of the fuselage the limiting cases are either sharp deflection of the rudder or the horizontal gust, whichever gives the greater value of sideways bending moment.

In structural analysis the above considerations allow many load cases being ignored in the preliminary stage of the design, since they have no significant influence on the dimensions of the structural members.

7. HORIZONTAL TAIL

Among the cases of horizontal tail load the most significant are:

- sharp deflection of elevator
- vertical gust
- forces necessary to achieve the periphery points of the envelope: A_1, B_1, C_1 and D_1.

Tab II

Glider	Type of tail	Sharp deflection of elevator on V_m: β_e°	Sharp deflection of elevator on V_m	Sharp deflection of elevator on V_D: β_e°	Sharp deflection of elevator on V_D	Vertical gust: U [m/sec]	Vertical gust	Points of envelope: A	B	C	D
		Horizontal tail loading P_H [kG]									
SZD-19-2A Zefir-2	elevator	-29,5	-161,3	-10,1	-165,1	-30	-81,4	-72,5	-71,5	-47,8	-32,4
SZD-21-2B Kobuz-3	-"-	*)	-298	*)	-345	-30	-149,4	-91,4	-230	-152	-124
SZD-24-4A Foka-4	-"-	-29,0	-133,6	-10,0	-220,4	-30	-110,1	-22,8	-66,5	-96	-52,8
SZD-27 Kormoran	-"-	-26,4	-233,9	-6,5	-260,3	-4	-209	-20,3	-86	-153	-125
SZD-29 Zefir-3	All moving	-16,5	-216,5	-3,2	-253,6	-30	-165,3	-45,8	-99,6	-93	-21,7
SZD-30 Pirat	elevator	-27,1	-135,9	*)	-181,1	-4	-161,3	-74	-117,7	-109	-61,2

*) The forces calculated assuming a deflection preventing the exceeding of load factor given by the periphery of n-V envelope.

Loads for several example gliders are presented in table II. The highest loads appear mainly in the case of sharp deflection of the elevator at speed V_D when the tail load is directed downwards. It is not, however, the limiting case for both the elevator and stabilizer. To answer that question it is necessary to calculate the pressure distribution along the chord. In the case of sharp deflection of the elevator the most common shape of pressure distribution (for negative deflection) is shown on fig. 32 where:

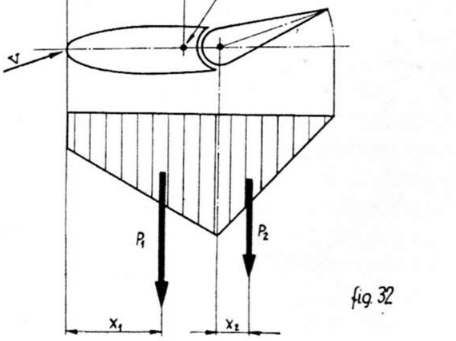


fig.32

- P_1 – force on stabilizer
- P_2 – force on elevator
- x_1 – distance between P_1 and stabilizer nose
- x_2 – distance between P_2 and elevator nose
- x_3 – distance between stabilizer centre of twist and nose

The shapes of pressure distribution for the gust case and for point C_1 of the envelope are presented on figs. 33 and 34 respectively. The results of pressure distribution calculations performed for the SZD-30 «Pirat» glider are noted in table III. For this machine elevator

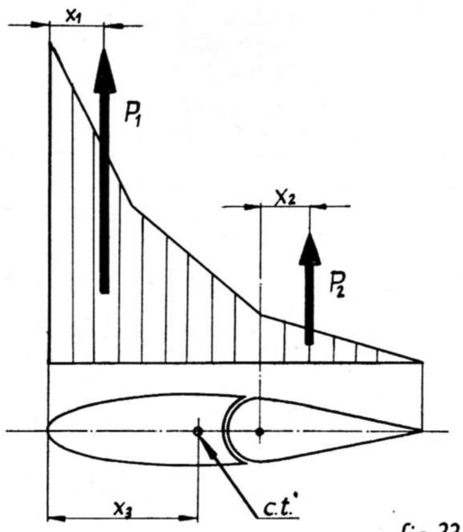


fig.33

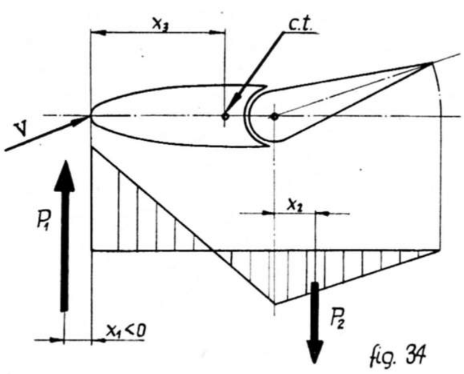


fig. 34

bending is greatest for the vertical gust case (the greatest value of force P_2, in this case negative) but torsion is a maximum for the case of sharp deflection of the elevator at speed V_D where the expression $P_2 \times x_2$ has the greated value. In most gliders the twist centre of the elevator lies near its nose because the torsion box is at the very front when the rear part is fabric covered.

Tab III

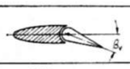
SZD-30 Pirat — Case of loading	Stabilizer: P_1 [kG]	Stabilizer: x_1 [chord per cent]	Elevator: P_2 [kG]	Elevator: x_2 [chord per cent]
Vertical gust U=-4 m/sec	-169,6	19,2	8,3	33,3
Sharp deflection of elevator V_D	-165,1	29,9	-16,0	33,3
Point C of n-V envelope	-128,8	9,1	19,8	33,3

The bending strength of stabilizer is undoubtely governed by the case of sharp deflection of the elevator at speed V_D as a consequence of action of forces P_1 as well as P_2. The last one is applied via the elevator hinges.
The torsional strength of the elevator is governed by the greatest value of force P_1 with respect to the triangular load distribution. The stabilizer torsion is governed by this case which gives the greatest value of expression $P_2\,(x_3-x_1)$ assuming that in common practice the distance between the centre of twist and the hinge points is fairly small, so that the influence of the elevator hinge reactions on torsion is slight. In all other cases this influence cannot be neglected. In most example gliders the worst cases for torsion are either the gust case or point C_1 of the envelope.
The general conclusion of above the considerations is that the strength governing cases for the horizontal tail unit are: vertical gust, sharp deflection of elevator at speed V_D and point C_1 of the envelope. The detailed analysis of load distribution along the chord allows further cases to be eliminated

8. VERTICAL TAIL

The symmetry of airfoil and rudder deflections on the vertical tail yields equal values of forces acting in both right and left direction. The most severe cases of vertical tail loads are presented in table IV. These are: sharp deflection of the rudder at speed V_D or V_m and the horizontal gust. The greatest value of load can occur either in the gust case (SZD-27 Kormoran, SZD-32 Foka-5) or in the sharp deflection of rudder case at V_D (SZD-21-2B Kobuz-3, SZD-24-4A Foka-4, SZD-29 Zefir-3, SZD-30 Pirat).

Tab IV

 Glider	Vertical tail loading P_V [kG]				
	sharp deflection of rudder on V_m		sharp deflection of rudder on V_D		horizontal gust
	β_V°		β_V°		
SZD-19-2A Zefir-2	30	88,6	10	106,3	88,1
SZD-21-2B Kobuz-3	30	144,3	10	292,1	244,8
SZD-24-4A Foka-4	35	62,5	11,7	93,7	88
SZD-27 Kormoran	30	83,9	10	95,3	154,3
SZD-29 Zefir-3	30	158,8	10	270,7	192,6
SZD-30 Pirat	35	106,0	11,7	149,0	128,0
SZD-32 Foka-5	27,6	66,8	9,2	71,0	124,7

Results of load distribution effects are gathered in table V as numerical values

Tab V

Glider	sharp deflection of rudder on V_D				horizontal gust			
	FIN		RUDDER		FIN		RUDDER	
	P_1 [kG]	x_1 [chord per cent]	P_2 [kG]	x_2 [chord per cent]	P_1 [kG]	x_1 [chord per cent]	P_2 [kG]	x_2 [chord per cent]
SZD-21-2B Kobuz-3	109	24,8	183,1	33,3	175	17,5	69,8	33,3
SZD-24-4A Foka-4	49,3	60,0	44,4	33,3	78,1	32,2	14,9	33,3
SZD-29 Zefir-3	132,7	36,3	138	33,3	157,1	33,0	-95,5	33,3
SZD-30 Pirat	77,3	62,0	65,7	33,3	106,0	39,1	22,0	33,3

for P_1, P_2 and x_1, x_2. The limiting case for fin bending appears to be either the horizontal gust or sharp deflection of the rudder at speed V_D. Fin torsion is limited by the gust case. Both bending and torsion of the rudder are limited by the case of sharp deflection at V_D. The above conclusions are based on the same philosophy as employed in the discussion on the horizontal tail.
The general conclusion of vertical tail load considerations is that the governing cases for fin and rudder loads are: horizontal gust and sharp deflection of the rudder at speed V_D.

9. CONCLUSIONS

At the very beginning of the design process it is very interesting to know which load cases are the governing ones for particular components of the glider. Design experience allows a great number of load cases to be eleminated to obtain only the most severe, which decide the dimensions for particular members of the glider being designed. In the preceding paragraphs are discussed the loads on wing, aileron, flap, fuselage and tail unit. For every component are analyzed the main loads and their influence on strength considerations discussed. The governing cases were emphasized. A summary of the results obtained is as follows:

Wing
- point A of envelope in upwards bending
- point D of envelope in downwards bending in the case of wooden or orthotropic material designs
- point C of envelope in the case of low torsional stiffness of the wing, or high value of speed V_D

Aileron
- full down deflection of aileron in normal flight
- full up deflection of aileron in inverted flight

Flap
- flight at speed V_F with load factor n_{F2}

Fuselage
- tow rope loads for front part
- points A and D of envelope for central part
- sharp deflection of elevator or point D of envelope or touch landing for rear part

Tail unit
- sharp deflections of control surfaces at speed V_D
- gusts
- point C_1 of envelope (for horizontal tail only)

The detailed limiting cases depend on the shape of the pressure distribution along the chord.

All the above remarks are to be treated as recommendations for the designer in tracing the first approach to the shape and structure of the glider under design. The full technical ducumentation requires, of course, the accurate analysis of loads for the full range of loading cases.

REFERENCES:

1. A. Skarbinski, W. Stafiej «Projektowanie i konstrukcja szybowców» WKi Warszawa 1965.
2. Zeszyty Instytutu Lotnictwa Nr. 4/1957.