DESIGNING A CRASHWORTHY COCKPIT SILL.

Proposal for an acceptable means of compliance according to OSTIVAS or JAR-22.

By Dipl.-Ing. Gerhard Waibel, A. Schleicher
Segelflugzeugbau GmbH u. Co., Poppenhausen

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SUMMARY

Statistical examination of sailplane crashes has demonstrated that the cockpit structure is destroyed during major crashes in the region of the pilot's seat. The cockpit sill buckling outwards is considered as the most likely cause of this failure.

This paper describes a calculation method applicable for designing a cockpit sill sufficiently strong to withstand high impact crash forces. The design method also shows strategies which help to support this component, without a considerable weight penalty being incurred.

HISTORICAL REVIEW

Statistical survey of sailplane crashes done by Dipl.-Ing. Martin Sperber of TUV Rheinland, Cologne, Germany, see [Lit. 1], has shown that for most sailplane designs the cockpit sill fails first during major ground impact crashes. However the fuselage structure in front of the pilot and behind the cockpit is less damaged.

The author of this paper succeeded in better balancing stiffness and impact strength of sailplane cockpit structures, so that the fuselage structure in front of the pilot absorbs energy and the cockpit sill withstands higher loads, see [Lit. 2]. An important detail of this effort was the development of a calculation method, used to design the cockpit sill.

FUTURE DEVELOPMENTS

The very valuable paper of Crawley, Hansman and Kampf, which was acknowledged by OSTIV, with the title "Experimental Investigation of the Crash-Worthiness of Scaled Composite Sailplane Fuselages" presented at the XXI OSTIV Congress, [Lit. 3], as well as contributions of Detlev Pusch and Martin Sperber, TUV Rheinland Luftfahrt GmbH, [Lit. 4] and Prof. Dr.-Ing. Wolf Roger, P. Stabenau, M. Conradi, Fachhochschule Aachen and their students, [Lit. 5], have triggered the OSTIV SDP to write more detailed crash-worthiness standards for emergency landing conditions with a much higher load level and a failure mode, which should ensure with considerable likelihood, that the fuselage absorbs energy in front of the pilot while the seat area and the rear cockpit withstands high crash loads.

PROBLEM AREAS

Physical testing of full scale fuselages is expensive, dynamic testing even more than static testing. Therefore OSTIV-SDP is encouraging the development of reliable calculation methods of compliance. It would be wonderful if someone could present a cheap and acceptable, "Finite Element Code" to design sailplane cockpits.

Until we have such a code, design criteria as well as appropriate calculation methods and eventually a simple "quasistatic" test must help to design the critical components of the cockpits.

PROPOSAL

It is proposed to simulate the cockpit sill as a laterally curved, elastically supported beam under compression load.

It is the intention of Airworthiness Requirements like OSTIV-AS or JAR-22 to determine minimum strength for the cockpit in a load case representing highest forces to the occupant's compartment in the crash scenario experienced from accident investigation statistics. Recently OSTIV-SDP has specified more detailed requirements in OSTIVAS. Much higher accelerations must be demonstrated for the cockpit area where the pilot is tied-in whereas the structure in front of the pilot or occupant must fail at lower accelerations, and the structure (or an extended engine) behind the pilot may fail, but only in such a way that the occupant is not endangered by these components.

As an example the calculation according to JAR 22.561 (b)(2) is given hereafter. A calculation according to OSTIV-AS would be substantially the same, but with higher loads and varying stations where the loads apply. This method of calculation is quite successful for designing cockpit sills of sufficient strength and also gives insight into the main parameters, which may be varied to make a stiff and strong cockpit at reasonable weight.

Figure 1 illustrates the requirement text of 22.561(b)(2) which reads: "An ultimate load of 6 times the weight of the sailplane acting rearwards and upwards at an angle of 45° to the longitudinal axis of the sailplane on the forward portion of the fuselage at the foremost point(s) suitable for the application of such a load."
It is up to the designer where the contact point of $P = 6mg$ is situated. It is proposed to use the position of the heels of a tall occupant as this point, also in order to comply with 22.561 (a) and the interpretative text of (b).

Usually only the vertical component P_z of P must be regarded as the compression loads caused by the horizontal component P_x of P are small and may be neglected.

$$M_y = P_z . a = 0,707.6.m.g.a \quad (1)$$

Note: Distance 'a' must be chosen in such a way, that the occupant is not hurt in case of a crash.

It is obvious, that the load of the cockpit sill considerably increases from the front to the rear end. However, this is not important for the following calculation. Experience shows, that sills fail about in the middle and that is, where reinforcement is necessary. Nevertheless it is good to keep in mind, that the loads in the front part are lower continuously increase rearwards, so that an adequate design of strength along the sill can be verified.

Figure 2 illustrates the fuselage cross section at the critical fuselage station (as experienced from accident statistics). Upper as well as lower part of the cockpit shells take half of the bending moment My. Two equivalent (fictive) beams replacing the upper half of the section have to take the role of the shell. So for each one

$$P_{BEAM} \bullet b = /4\, M_y \quad (2)$$

It is up to the designer to choose a good location of the equivalent beam replacing the cockpit wall and sill. There is little chance to cheat with the beam position. But it is important to notice, that a high cockpit side wall results in a high moment of inertia I_y, which reduces the stress level for a given bending moment M_y.

Figure 3 shows the cockpit from above. It is now obvious, why the station in the middle of the cockpit sill is most critical. It is the station where the beam, simulating the cockpit sill is maximally bent outwards relative to a straight line connecting front and rear end of the beam. It has proven to be successful to replace the cockpit sill by this equivalent structure, which is a curved beam under compression load P_{BEAM} and elastic lateral support.

A curved beam under compression load without elastic support would have to be unrealistically strong. Only in case of a steel tube frame work design of the fuselage a big tube compared to its neighbors is capable to withstand this load.

Note: A straight beam will carry slightly higher loads, but it may buckle inwards into the cockpit and severely hurt the crew in a crash. So an intentional outwards curvature is strongly recommended for all tubes, bulkheads and stringers.

The real cockpit sill however is not an unsupported beam. It is quite stiffly supported in Z direction but not so much in Y - direction. However cockpit walls and / or bulkheads have the effect of an elastic support. That may be simulated by one or more springs or even continuous elastic support.

It is also important to consider the conditions at the ends of the beam. How are those supported? Are they a flexible joint or are they stiffly connected to the rest of the structure in bending? For conservative calculation it is suggested to assume flexible joints which can only transfer forces but no bending moments. Especially when the fuselage nose in front of the beam is destroyed any controlled support in bending is lost. For the rear end however bending stiffness in Z - and Y - direction is very important. For the straight beam with one rigidly fixed end the effective buckling length is reduced to 70% or the buckling load is doubled. Also the station of the highest deformation is shifted to forward of the middle of the beam, see Figure 4.

In his full scale crash tests Martin Sperber also found, that the rigid fixing of the cockpit sill at its rear end is very important for strength of the cockpit and also the fuselage wall behind the cockpit must not buckle. He recommends to extend the cockpit sill reinforcement stringer to the rear fuselage main bulkhead, see [Lit. 1].

The differential equation for the curved beam with continuous elastic lateral support under compression load reads:

$$E.l.w'''' + P.w'' + k.w = P.w_o'' \quad (3),\text{where}$$

E is the modulus of elasticity of the beam material,
l is the moment of inertia of the (constant section) beam,
w is the additional lateral bending deformation of the beam due to load P,
P is the (constant) compression load of the beam,
k is the stiffness of the continuous elastic support and
w_0 is the eccentricity (or initial offset) of the beam.

For the straight beam under compression with elastic lateral support the differential equation is :

$$E.l.w'''' + P.w'' + k.w = 0 \quad (4)$$

as well as for the curved beam under compression without support:

$$E.l.w'''' + P.w'' = -P.w_0 \quad (5)$$

Some solutions are known for equations (4) and (5) which simplify the problem of solving the more complex differential equation (3) before.

Assuming, that the curve of the unloaded beam simulating the cockpit sill is a half sine wave with the amplitude w0, the total amplitude $w + w_0$ under the compression load P is:

$$w + w_0 = w_0 / (1 - P/P_c) \quad (6)$$

where P_c is the critical buckling load under compression of (Euler's) straight beam.

$$P_c = E.\, l.\, \pi^2 / L^2 \quad (7)$$

where L is the length of the cockpit sill or equivalent beam.

The support conditions at the front end of the cockpit sill (or of the equivalent beam) cannot be determined in a crash scenario, as they may change when the fuselage nose is destroyed, as discussed above. No support or fixing at all is something like a worst case, provided no adverse bending moment is acting at this forward part, which increases the bending moment on the cockpit sill. To avoid this case the moment of inertia of the cockpit sill must not be too high or even should be intentionally reduced at the forward part, when compared to the middle section. The rear end of the cockpit sill should be rigidly fixed to the rest of the structure of the fuselage and the designer must not forget, that the fuselage skins behind the cockpit must not buckle. This can be achieved by continuing the cockpit sill as a stringer of the fuselage, see [Lit. 1].

The elastic support factor k or the stiffness C of a single spring can be determined by a rather simple test. Pull both cockpit sills outboard in the middle, measure force and deflection. The measured force divided by the deflection of one side under this load is the factor C of the spring. In case of the ASW-15 we have made a fuselage without the cockpit sill reinforcement and have measured the stiffness, see Figure 5, which was possible at that time. For later sailplane models the stiffness including the reinforcement was measured and the bending stiffness of the cockpit sill itself was determined by calculation and subtracted from the measured values.

The differential equation given before however demands for a continuous sideways support. A correction factor is necessary.

The deformation of a beam supported at its ends with a single perpendicular load in the middle reads:

$$w, = F. L^3 / E .1.48. \quad (8)$$

The deformation of a beam as above but with the load P distributed over the length L

$$p = F/L \quad (9)$$

is smaller and reads:

$$W_2 = F . L^3 . 5/E .1. 348, \quad (10)$$

so that the correction factor is 348/5 . 48 = 1,45, by dividing equation (8) through (10), or

$$k = 1 ,45 F / w, . L \quad (11)$$

The solution of the differential equation (3) for the curved beam with continuous elastic support under a compression load P is given by Mr. Robert Fessler, University of Basel, Switzerland as follows:

$$E. I .w'''' + P.w'' + k.w = P.w_o'' \quad (3), \text{ where}$$

$$w(0) = w''(0) = w(L) = w''(L) = 0 \qquad (12).$$

Assuming, that the curve of the beam simulating the cockpit sill is a half sine wave with the amplitude w_0 (no load condition) as before, then:

$$w_O(x) = a_O . \sin(\pi . x/L) \quad (13)$$

and introduce

$$w(x) = a. \sin(\pi . x/ L) \quad (14)$$

into our differential equation, Robert Fessler found

$$w(x) = \frac{a_0 . \sin(\pi . x / L)}{\dfrac{P_c + k(L/\pi)^2}{P} - 1} \quad (15),$$

where P_c is Euler's load of a straight beam, see (7) above and w(x) is the additional deformation due to load P.

In case of the ASW-15 calculation in the middle of the sill, where

$$x = L/2, \sin(\pi / 2) = 1 \text{and } a = w_O. \quad (16)$$

The other data are for the ASW-15 are: (17)

$P = 11\,500$ N,
$L = 120$ cm,
$w_O = 1{,}5$ cm,
$P_c = 1600$ N,
$k = 12{,}08 \text{ N} . \text{cm}^2$

$$W_{middle} = \frac{1{,}5}{\dfrac{1600 + 12{,}08 .(120/\pi)^2}{11500} - 1} = 2{,}232 \text{ cm.}$$

This is a very reasonable value. With this deformation one can check whether there is a reserve for higher deformation.

Note: Only solutions for w are possible, when $P_c + k(L/\pi)^2$ is greater than P.

For $P_c + k(L/\pi)^2 = P$ the instability is reached and the most elastic beam will fail.

From the above example it is apparent, that it is much more effective to improve the elastic support of the cockpit sill, than to reinforce the sill itself. P is about 7 times greater than P_c. A stiffer support of the cockpit sill can be obtained by inserting a bulkhead as high as practical under the knees of the occupant which will restrain the side walls from bending outboard, an additional stringer on the side of the cockpit wall (armrest) and some more screws, which hold the seat pan in place will provide some additional stiffness, etc.

CONCLUSIONS

- Try to make the cockpit side wall as high as practical. For improved view out of the cockpit additional windows below the cockpit sill can be added if necessary. A higher cockpit sill must not impair emergency bail out. Note that bail out is rarely necessary from level flight. Emergency bail out is more likely to occur in a pitch down attitude combined with some yaw.
- Make the canopy as small as practical in order to make the cockpit sill as short as possible.
- Do not make the cockpit sill straight. Outward curvature ensures that the sill fails outboard under excessive compression loads.
- Try to increase lateral stiffness of the cockpit by bulkheads. Elastic lateral support of the cockpit sill is more effective than reinforcement of the sill itself.
- Continue the cockpit sill reinforcement as a stringer into the wing-to-fuselage intersection.
- Make sure that the fuselage skin behind the cockpit does not start buckling prior to buckling of the cockpit side walls.

- Design the rear end of the cockpit sill in such a way, that it is also stiff in bending and well attached to the fuselage area behind.

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Gerhard Waibel c/o A. Schleicher GmbH & Co. D-36163
Poppenhausen, Germany.

APPENDIX: Figures 1 through 5.

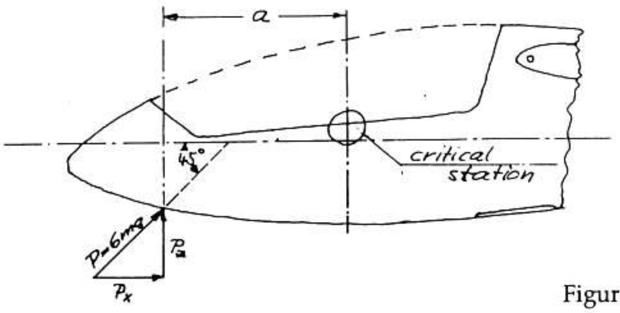

Figure 1

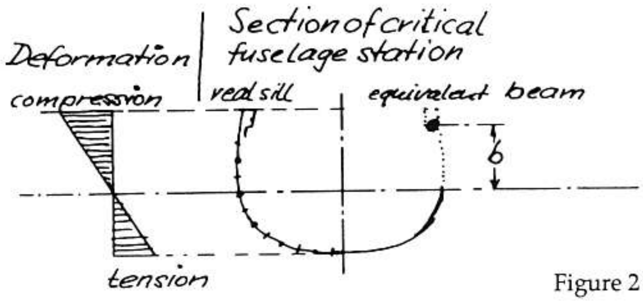

Figure 2

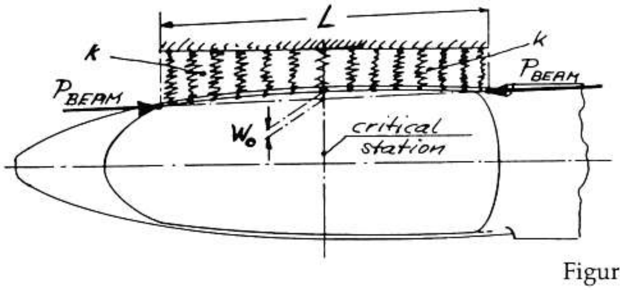

Figure 3

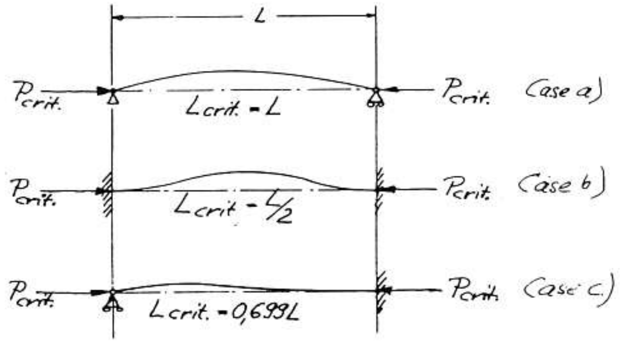

Figure 4. Critical Length

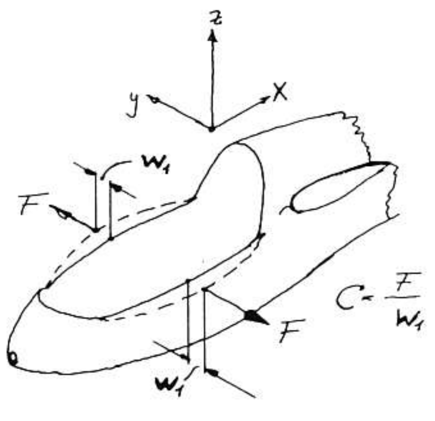

Figure 5