FAILURE ANALYSIS OF AIRCRAFT WINDSHIELDS SUBJECTED TO BIRD IMPACT

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Summary

Aircraft flying at high speed at low level altitudes run a high risk of bird collision and a number of aircraft accidents each year may be attributed to bird impact. In particular, windshield failure is of concern since it invariably involves pilot injuries. A comprehensive investigation was, therefore, carried out by the Swedish Air Force in order to define the operational envelopes of it's aircraft with respect to bird impact. The dynamic behavior of a windshield was studied by means of both linear and non linear theories and the results were verified by comparision with test results at the Saab Scania test range. It was shown that a linear analysis was adequate in most of the cases studied. This fact greatly reduced the cost of mapping the stresses of the windshield as function of impact velocity, bird size and target point. The report summarizes the theoretical background, the verification of the method of analysis and gives the result obtained for the Saab SK60 Trainer Aircraft.

1. Introduction

Bird impact analysis by use of Finite Element Methods (FEM) was first carried out at AFFDL in Dayton, USA, See Refs(1-4), as a design tool.

The MAGNA computer code, Ref(5), was specifically developed for this purpose, and it's applicability to complicated bird- wind-shield impact problems was demonstrated for a number of different US Aircraft windshields. The various levels of 'sofistication' needed in the analalysis of large deflection problems were demonstrated, Ref(2), and the results presented showed excellent agreement with experiments. In some cases spectacular results were derived with deflections of the order ot ten times the windshield thickness.

In Sweden, the birdstrike capacity of aircraft windshield was demonstrated only experimentally until about 5 years ago. In connection with a test series with the object to verify the long term strength of the windshields of one of the Swedish fighter planes, a contract was awarded 3K Acoustics by the Swedish Air Force to to analyze the problem theoretically and to compare the results with the test results obtained at Saab Scania Aircraft Co. The investigation was carried out in close cooperation with Saab and some of the results were presented in Ref(6) and Ref(7).

One of the main conclusions arrived at during the investigation was that, for the types of windshields used on Swedish aircraft, a linear dynamic analysis was adequate for mapping of the risk of failure due to bird size, velocity and point of impact. This result was as a matter of fact based on the comprehensive test series carried out by Saab. Some of the early work on fighter aircraft windshield analysis was presented in Ref(8). The present paper concerns failure analysis of the SK60 trainer windshield in order to establish safe operating limits with respect to bird impacts.

2.Theory

The theory of static and dynamic analysis of structures is well established and is being utilized in a large number of general pupose computer codes, Refs(5,9-11). Many of these codes have the cabability to analyze problems involving large strains, large displacements and rotations, nonlinear material characteristics etc. There will be no attempt to summarize these theories, only some of the characteristics of the methods used in the present results will be briefly discussed. Moreover,the accarucy of the results is often more dependant on the finite element model used, the number of eigenmodes employed and the load history representation than the particular theoretical formulation.

2.1 Dynamic analysis:

A finite element model for dynamic analysis may be analyzed by use of 'standard' model superposition techniques or by use of direct time integration methods. The first method involves solution of an eigenvalue problem yielding the eigenfrequencies of the structure and their associated eigenmodes. Subsequently, the dynamic response of the structure subjected to transient loads may be studied in the reduced modal coordinates and the total response is obtained by superposition of the time histories of the different modes. In the present analysis, the computer programme of Ref(11) was used for the eigenvalue analysis. Subsequent respons analyses were done in a set of specialized routines in order to facilitate mapping of the relevant parameters as functions of the input variables such as bird size, impact point and velocity. A brief summary of the theory for the modal analysis is given below:

Assume that the eigenvalue problem for the windshield has been solved yelding the generalized coordinates $\bar{q}_{kn}$ and the eigenfrequency $\bar{\omega}_k = \omega_k (1+i\eta)$, k=1,..n. Then a linear system of equations for the dynamic problem is given by

$$\ddot{\bar{q}} + \omega_k^2 \bar{q}_k = B_{zk} F_z(t) \qquad (1)$$

where B_{zk} is the component of eigen vector corresponding to a z-displacement at the impact point to Fig 1. $F_z(t)$ is the force acting at point k.
The displacement at the impact point is given by

$$u_z = Re[\Sigma B_{zk} \cdot q_k] \qquad (2)$$

and the velocity by

$$v_z = Re[\Sigma B_{zk} \cdot \dot{q}_k] \qquad (3)$$

Eqs (1-3) are sufficient for the solution of the dynamic response problem.

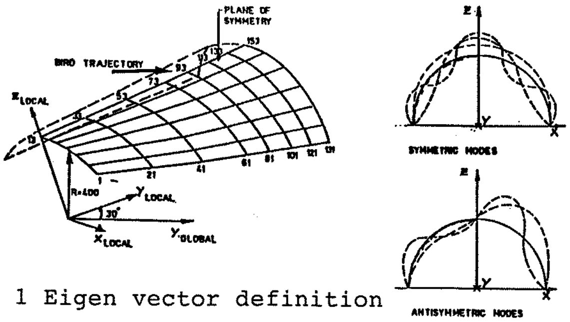


Fig 1 Eigen vector definition

An alternative to the modal superposition technique is the direct integration method, where a number of different integration techniques are available. Direct integration is, however, the only possible solution method in nonlinear analysis (large displacements, elastic-plastic material etc) and this is where it's main application may be found. Detailed descriptions of the method may found in Ref(5) and the discussion in the present paper will be limited to the results obtained.

2.2 Failure criteria

The properties of transparent materials were accepted from Ref(12) giving Young's modulus, yield and ultimate stresses and Poisson's ratio obtained from one-dimensional tests. In the evaluation of a 'characteristic' stress it was assumed that the tensile stress would best represent the tensile stress in uniaxial tension and was thus used to estimate the 'point of' fail- lure. In most cases this may lead to a slightly conservative result in comparison with using the von Mises stress.

Bird collission involves transient deformation at an extremely high strain rate. Few test values are available on the effect of the strain rate on the ultimate stress. It is possible that use of the static values may lead to a slightly conservative estimate of the failure load.

Other parameters may be critical in a bird strike situation. Since the deflections usually are fairly large, the windshield may hit structural parts such as a head up display, camera housing etc. Such events most likely trigger fracture of the windshield and must be avoided.

The condition and age of the windshield are parameters which must be considered, In particular small edge cracks may propagate as a result of a bird collision.

2.3 Loading history

The dynamic loading caused by a bird collision may be extremely complex and routines for a rigorous coupled analysis were not available. Such routines are being developed, see Refs(1,4). Approximate methods have been developed according to Ref(1). These methods are based on test results and may be assumed to yield results accurate enough for the present purpose.

According to Fig. 2 the force perpendicular to the windshield surface may be calculated from

$$F(t) = \begin{matrix} 10F_{avg}\left(\frac{t}{T}\right) & 0 \leq t \leq 0.2T \\ \frac{5}{2}F_{avg}\left(1-\frac{t}{T}\right) & 0.2T \leq t \leq T \end{matrix}$$

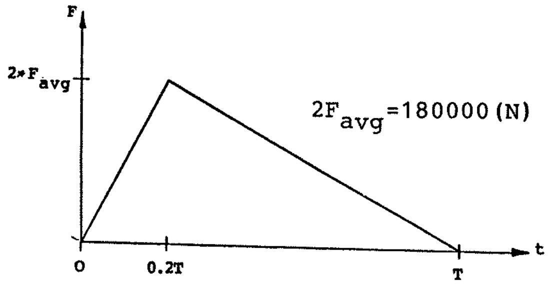


Fig 2 Load time function for the SK60 windshield

Due to the deflection of the windshield, the load application point moves along the surface and in highly nonlinear problems the effect has to be considered. In the present case the load appliction point was assumed to be 'stationary'. Cases where updating of the load was essential are described in Ref(2).

3.Verification of the method of analysis.

Numerous analyses were carried out for comparison with test data for the F35 and F37 fighter aircraft. Some of the data were presented in Ref(6). Additional results are given in Fig 3 and Fig 4.

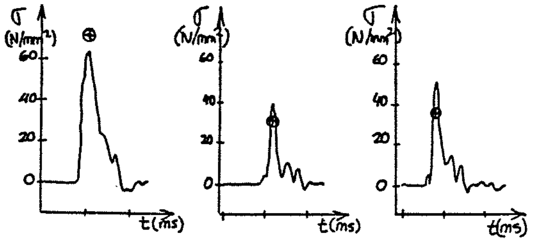


Fig 3 Measured vs calculated stresses F37 Aircraft windshield

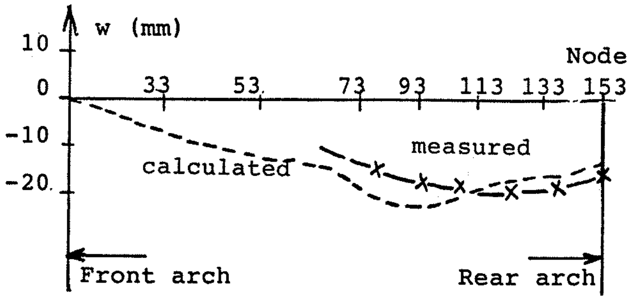


Fig 4 Maximum deflection measured on an F35 Aircraft windshield

Fig 3 shows the stresses measured and calculated at a few locations on an F37 aircraft windshield during bird impact. Fig 4 shows the maximum deflection measured on an F35 aircraft windshield and the estimated envelope by use of linear modal superposition. The differences are mainly due to the fact that the preassure load travels backward in the real situation, while the simulation assumed a stationary load application point. The agreement between theory and experiments was found to be acceptable.

An interesting result was found in one impact analysis of the F35 windshield where the maximum stress was found to develop at the lower aft corner as shown in Fig 5. Failure did occure at that location in the tests at Saab as was shown in Ref(8).

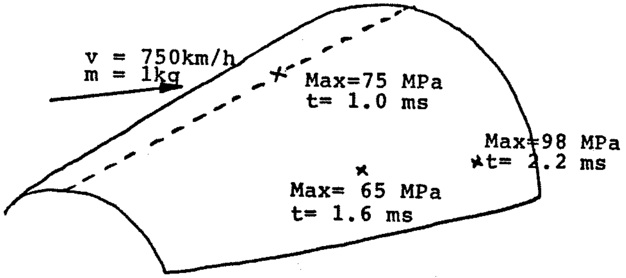


Fig 5 Calculated maximum stress i an F35 aircraft windshield

Nonlinear analyses carried out by use of MAGNA, Ref(5), showed that large deflections had an effect on the accuracy of the results. The influence was, however, relatively small in the cases studied and it was decided to use the modal superposition technique to map the failure characteristics of the windshield. The result of the nonlinear studies were included in Ref(6).

4. Analysis of Trainer Windshield.

4.1 Model

The geometry of the Saab SK60 Trainer windshield is given in Fig 6.

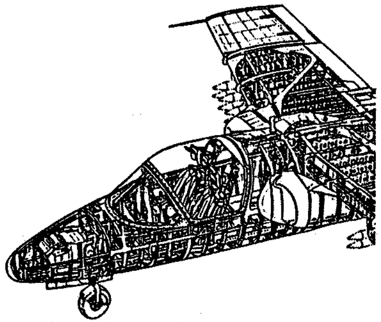


Fig 6 SK60 windshield and canopy configuration.

A finite element model was developed according to Fig 7 where the experience from earlier analyses of Ref(6) and Ref(8) was applied. Thus the windshield was assumed to be simply supported along the sill and was attached to the rear arch modelled as a beam. The influence of the canopy was neglected. Based on earlier results only symmetric impact cases were studied.

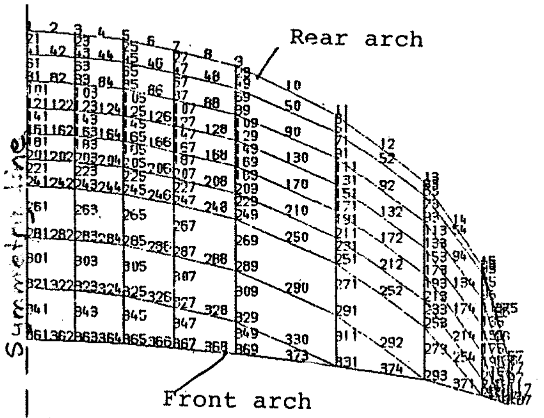


Fig 7 Finite element model of SK60 windshield. Node numbering.

4.2 Eigenmodes and frequencies.

The dynamic properties of the windshield were calculated by use of eigenvalue analysis and a total number of 10 eigenmodes and frequencies were extracted. Some of these are shown in Fig 8a-b. It may be noted that the highest eigenmode considered contains a total of 22 half waves along the symmetry line. The model will, therefore, not give accurate results for small bird impacts since the resulting short wavelength can be modelled only if higher modes were to be included. On the other hand, the results are not very sensetive to the load distribution as demonstrated in Ref(8) and application of a point load should give accurate results.

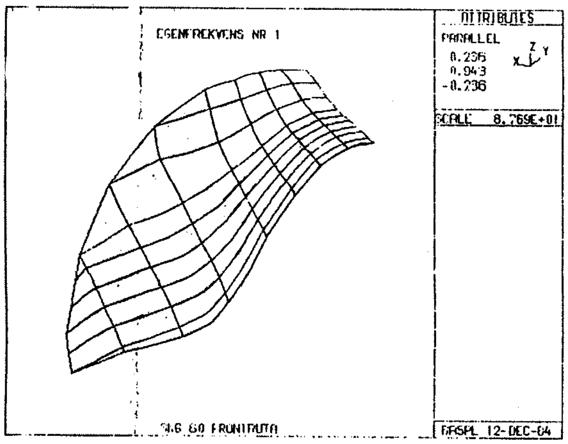


Fig 8a Eigenfrequency no 1, SK60 windshield

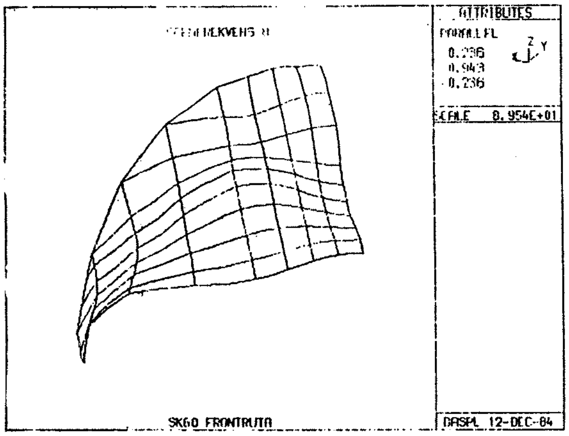


Fig 8b Eigenfrequency no 8, SK60 windshield

The eigenfrequencies are somewhat lower than those obtained for the two fighters, Ref(6) which should be expected due to the slightly more flexible design.

4.3 Dynamic response analyses.

The dynamic response was evaluated in a number of impact problems involving 1 kg birds and various impact points and velocities. Sample results of the deflection history are shown in Fig 9 and Fig 10. It is evident that deflections of the order of the windshield thickness may be anticipated for relatively modest impact velocities. This implies that care should be taken not to place objects closer to the windshield than approximately 30 mm.

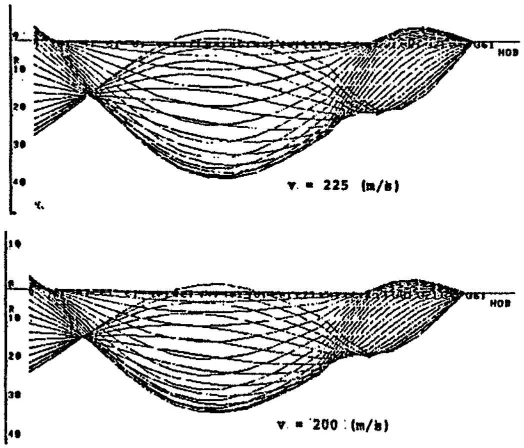


Fig 9 Sample results of deflections along symmetry line, $0 \leq t \leq 2.5$ms $m = 1.0$kg

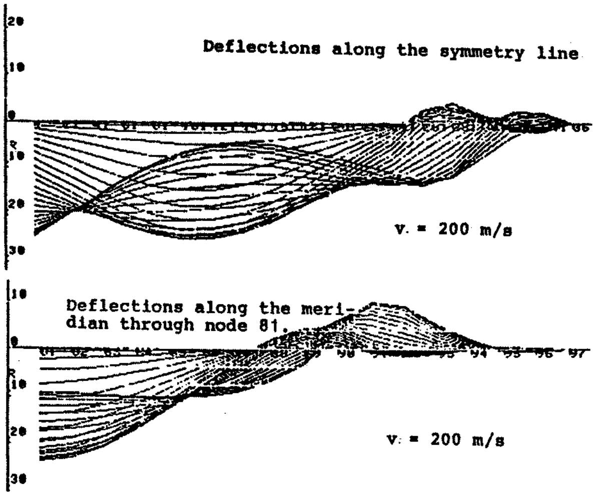
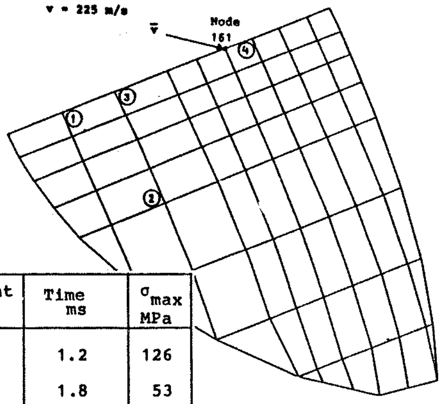


Fig 10 Sample results of deflections along the symmetry line and the meridian through hit node 81. m=1.0kg

Mapping of the maximum stresses was done for a number of cases yelding results as indicated in Fig 11.



Pos	Element nr	Time ms	σ_{max} MPa
1	53	1.2	126
2	56	1.8	53
3	47	2.2	84
4	24	2.5	141

Fig 11 Mapping of the maximum stresses SK60, v = 225 (m/s), m = 1.0 kg hit node 161.

As was found in the earlier studies, the maximum stress is a function of the impact point location. This is even more evident from Fig 12 summarizing the results of failure analyses for a 1 kg bird as functions of the impact velocity. These differences may, to some extent, be attributed to the fact that the analysis is based on a finite number of eigenmodes. However, the the effect was clearly demonstrated in the tests carried out on the A37 windshield and the results should, therefore, be relevant.

4.4 Influence of bird size.

For bird sizes around 1 kg, the analyses showed that the kinetic energy may be used as a measure of the critical impact parameter. For very large size birds, the footprint on the windshield will be comparable to the wavelength of the lower nodes and large errors may result. The extrapolation based on the impact energy is estimated to yield acceptable results for bird sizes of 0.7 < m < 2 kg.

Small birds yield a very narrow footprint and the modal analysis technique used is not satisfactory. On the other hand it was shown in Ref(8) that the critical velocity may be estimated from the criterion that the shear stresses are exceeded. The criterion was used for bird sizes below 0.5 kg. In the transition interval a curve fitting procedure was used. The results are shown in Fig 12 where the critical velocity is plotted as a function of the bird size and the most critical impact point. For assessment of the risk of failure due to bird impact, diagrams of the form shown in Fig 13 may be developed. Such analyses were carried out for the F37 aircraft as demonstrated in Ref(7).

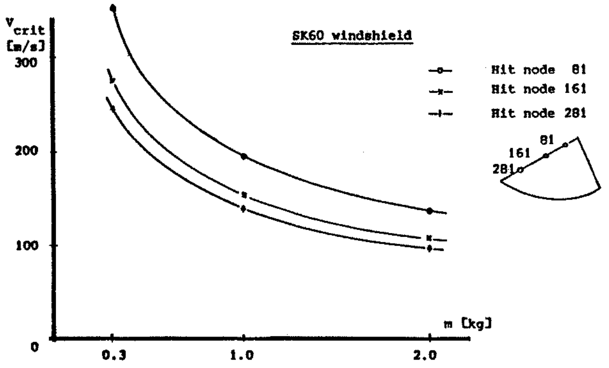


Fig 12 Critical velocity as a function of bird size and impact point. SK60 windshield.

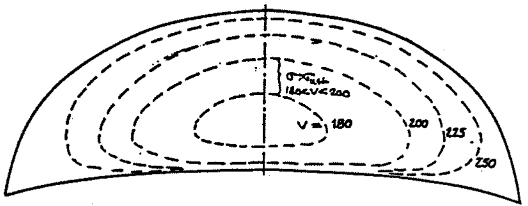


Fig 13 Approximate failure risk zone for the SK60 windshield involving a 1.0 kg bird.

5. Concluding remarks.

A brief discussion was given of the applicability of linear modal superposition analysis for high velocity bird impact problems. It was shown that for certain types of windshields the technique yields acceptable estimates of the critical velocity. It is important though to estimate the influence of geometrical nonlinearity on the results and to tailor the model and response analysis parameters to the problem to be solved. Verification by comparison with tests should be carried out in cases where expected deflections are larger than the windshield thickness.

References

(1) **West, B S, Brockman, R A,:**Evaulation of Bird Load Models for Dynamic Analysis of Aircraft Transparencies AFWAL-TR-80-3092, Aug 1980

(2) **Mc Carty, R E:** Finite Element Analysis of F-16 Aircraft Canopy. Dynamic Response to Bird Impact Loading. Proceedings of the AIAA/ASME/ASCE/AHS 21st Structures, Structural Dynamics and Materials Conference, Seattle Wash., May 12-14 1980.

(3) **Mc Carty, R E:** Aircraft Transparency Bird Impact Analysis Using the Magna Computer Program. Proceedings of the Conference on Aerospace Transparencies, London 8-10 Sept 1980.

(4) **Brockman R A:** Finite Element Analysis of Soft-Body Impact. AFWAL-TR-84-3035, Oct 1984

(5) **Brockman,R A:** MAGNA (Materially and Geometrically Nonlinear Analysis. Computer Program User's Manual, University of Dayton Research Inst. Dayton, Ohio. UDR-TR-80-107, 1980

(6) **Samuelson L A, Nilsson F, Sörnäs L,:** Theoretical Evaluation of the Structural Performance of Swedish Fighter Aircraft Windshields Subjected to Bird Impact. Proceedings of the Conference on Aerospace Transparent Materials and Enclosures, Scottsdale, Arizona. 11-14 July 1983.

(7) **Fonde'n, B P, Persson, K I:** Investigations Converning Improvements of the Saab 37 Windshield Birdstrike Resistance. Proceedings of the Conference on Aerospace Transparent Materials and Enclosures,Scottsdale, Arizona.11-14 July 1983.

(8) **Samuelson L A, Nilsson F, Sörnäs L:** Aircraft Windshield Bird Impact Analyses. IFM Akustikbyrån TR 5.200.01-04 (in Swedish).

(9) **Hibbitt, Karlsson and Sorensen:**ABAQUS

(10) **Bathe K J:**ADINA

(11) **Kjellberg S, Stehlin P, Palmberg B, Merazzi S:** BASIS -Finite Element Structural Analysis - User's Manual, The Aeronautical Research Institute of Sweden, Stockholm Febr 1979.

(12) **AFFDL Data sheet:** Issued at MAGNA short course, Dayton 1981.