Boeing 747-121, N739PA: Appendix D

Aircraft Accident Report No 2/90 (EW/C1094)

Report on the accident to Boeing 747-121, N739PA at Lockerbie, Dumfriesshire, Scotland on 21 December 1988

APPENDIX D

CRITICAL CRACK CALCULATIONS

It was assumed that the fuselage rupture and associated star-burstpetalling process was driven by an expanding 'bubble' of highpressure gas, produced by the conversion of solid explosive materialinto gas products. As the explosive gas pressures reduced dueto dissipation through the structure and external venting, theservice differential pressure loading would have taken over fromthe explosive pressures as the principal force driving the skinfractures.

The high temperature gas would initially have been confined withinthe container where, because of the low volume, the pressure wouldhave been extremely high (too high for containment) and the gasbubble would have expanded violently into the cavities of thefuselage between the outer skin and the container. This gas bubblewould have continued to expand, with an accompanying fall in pressuredue to the increasing volume combined with a corresponding dropin temperature.

The precise nature of the gas expansion process could not be determineddirectly from the evidence and it was therefore necessary to makea number of assumptions about its behaviour, based on the geometryof the hull and the area of fuselage skin which the high pressurebubble would have ruptured. Essentially, it was assumed thatthe gas bubble would expand freely in the circumferential direction,into the cavity between the fuselage skin and the container. In contrast, the freedom for the bubble to expand longitudinallywould have been restricted by the presence of the fuselage frames,which would have partially blocked the passage of gas in the foreand aft directions. However, the pressures acting on the frameswould have been such that they would have buckled and failed,allowing the gas to vent into the next 'bay', producing failureof the next frame. This sequential frame-failure process wouldhave continued until the pressure had fallen to a level whichthe frames could withstand. During the period of frame failureand the associated longitudinal expansion of the gas bubble, thisexpansion rate was assumed to be half that of the circumferentialrate.

It was assumed that venting would have taken place through theruptured skin and that the boundary of the petalled hole followedbehind the expanding gas bubble, just inside its outer boundary,i.e. the expanding gas bubble would have stretched and 'unzipped'the skins as it expanded. This process would have continued untilthe gas bubble had expanded/vented to a level where the pressurewas no longer able to drive the petalling mechanism because theskin stresses had reduced to below the natural strength of thematerial.

The following structural model was assumed:

(i) The pressurised hull was considered to be a cylinder of radius 128 inches, divided into regular lengths by stiff frames.

(ii) The contributions of the stringers and frames beyond the petalled region were considered to be the equivalent of a reduction of stress in the skins by 20%, corresponding to an increase in skin thickness from 0.064 inches to 0.080 inches.

(iii) Standing skin loads were assumed to be present due to the service differential pressure, i.e.. it was assumed that no significant venting of internal cabin pressure occurred within the relevant timescale.

(iv) The mechanism of bubble pressure load transfer into the skins was:

a) Hoop direction -conventional membrance reaction into hoop stresses

b) Longitudinal direction - reaction of pressures locally by the frames, restrained by the skins.

The critical crack calculations were based upon the generalisedmodel of a plate under biaxial loading in which there was an ellipticalhole with sharp cracks emanating from it. This is a good approximationof the initial condition, i.e.. the shattered hole, and an adequaterepresentation of the subsequent phase, when the hole was enlargingin its star-burst, petalling, mode.

The analyses of critical crack dimensions in the circumferentialand longitudinal directions were based on established FractureResistance techniques. The method utilises fracture resistancedata for the material in question to establish the critical conditionat which the rate of energy released by the crack just balancesthe rate of energy absorbed by the material in the cracking process,i.e. the instantaneous value of the parameter Kr, commonly referredto as the fracture toughness Kc. From this, the relationshipbetween critical stress and crack length can be determined.

Using conventional Linear Elastic Fracture Mechanics (LEFM) withfracture toughness data from RAE experimental work and publishedgeometric factors relating to cracks emanating from ellipticalholes, the stress levels required to drive cracks of increasinglengths in both circumferential and longitudinal directions werecalculated. The skin stresses at sequential stages of the expandinggas bubble/skin petalling process were then calculated and comparedwith these data.

The results of the analysis indicated that, once the large petalledhole had been produced by explosive gas overpressure, the hoopstresses generated by fuselage pressurisation loads acting alonewould have been sufficient to drive cracks longitudinally forlarge distances beyond the boundaries of the petalled hole. Thus,with residual gas overpressure acting as well, the 43 feet (totallength) longitudinal fractures observed in the wreckage are entirelyunderstandable. The calculations also suggested that the hoopfractures, due to longitudinal stresses in the skins, would haveextended beyond the boundary of the petalled hole, though theexcess stress driving the fractures in this direction would havebeen much smaller than for the longitudinal fractures, and thelevel of uncertainty was greater due to the difficulty of producingan accurate model reflecting the diffusion of longitudinal loadsinto the skins. Nevertheless, the results suggested that thecircumferential cracks would extend downwards just beyond thekeel, and upwards as far as the window belt - conclusions whichaccord reasonably well with the wreckage evidence.