Development of requirements, criteria and design guidelines for frangibility of structures at airports

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Abstract

An overview is presented of the approach that was followed to develop requirements, criteria, design guidelines and test methods for the frangibility of Approach Lighting Systems at airports. This work was carried out by the Frangible Aids Study Group of ICAO during the years 1983 – 2003, and has resulted in an updated Annex 14 "Aerodromes", with improved specifications for frangibility, and a newly created Part 6 "Frangibility" of the ICAO Aerodrome Design Manual in 2006. This overview may be useful for the development of requirements, criteria, design guidelines and test methods for the frangibility of other structures at airports.

1. Introduction

The operation of aircraft at airports requires the presence of equipment to assist pilots taking off and landing safely in nearly any weather condition. Support structures of those aids, which are necessarily located close to airport runways, create a potential risk to air traffic in general, and to the safety of passengers in particular. If an aircraft encounters problems during take-off or landing, and hits these structures accidentally, the resistance of these structures may well determine the outcome of such a mishap.

In 1971, a Pan American Boeing 747 struck the Approach Light Structure (ALS) at the departure end of runway 01R while taking off from the San Francisco International Airport [1]. The damaged areas of the aircraft included the left and right main body landing gear, including their respective wheel wells and doors, the aft cargo compartment and cargo containers, the inboard flap assemblies and flap wells, the inboard flap track canoe fairings No. 4, 5, and 6, the passenger compartment from BS1489 to BS2412, the aft pressure bulkhead, the left and right horizontal stabilizers, the right inboard and outboard elevator assemblies, the internal structure of the vertical stabilizer, and the right APU access door. Three pieces of 2" x 2" x .25" angle iron from the ALS structure penetrated the cabin, one of these pieces seriously injuring two passengers.

This accident may well have been the motivation for the FAA to invest in the development and testing of frangible approach light structures. In 1974, a test effort was reported [2] to determine the frangibility of a new ALS design (using an aluminium tube) and of existing commercially available metal approach light masts. In 1979, a further, successful test campaign was reported [3] of a newly developed frangible ALS support structure, that used a 6 inch diameter, glass fibre tubular pole with integrated frangible couplings. This pole concept has since been used for ALS support structures at airports in the US.

In order to develop international regulation for the frangibility of equipment or installations at airports, which are required for air navigation purposes (e.g., approach lighting towers, meteorological equipment, radio navigational aids, etc.) and their support structures, ICAO instigated the "Frangible Aids Study Group" (FASG) in 1981, with the task to define design requirements, criteria, guidelines and test procedures for the frangibility of such aids. This work was carried out in the 1983 – 2003 timeframe. During six official meetings, intermediate results were discussed and documents were updated. The outcome was an updated Annex 14 Aerodromes, with adapted specifications for frangibility, and a newly created Part 6 “Frangibility” of the ICAO Aerodrome Design Manual [4].

The present paper gives an overview of the steps that were taken to achieve the present regulation for the frangibility of structures at airports. This may be of use for future regulation of the frangibility for ILS glide path towers, as this has not been developed as yet.

2. Frangibility Requirements

The first meeting of the Frangible Aids Study Group took place in 1983, like all subsequent meetings at the ICAO office in Montreal under guidance of an ICAO rapporteur. Representatives of the airworthiness authorities and their advisors of seven countries participated in this group: the UK, Canada, US, Sweden, Germany, New Zealand, and the Netherlands. After the first meeting, Germany and New Zealand no longer participated.

The need for regulation for frangible structures close to runways at airports was clear from the start, however, the insight into the physics of aircraft impacting structures was limited. The knowledge available at the time was entirely based on the results of a full scale test programme on a frangible approach lighting tower, which was carried out for the FAA [3] at the Naval Air Engineering Centre at Lakehurst, NJ, in January 1979. The FAA required a frangible approach lighting tower concept to be developed and tested, which would “separate cleanly when impacted”, be able to resist the required wind loading, and be cost effective.

The test configuration consisted of an impactor built up on a rail car. This impactor was either a rigid impactor or a small aircraft wing, positioned at a height of approximately 5 meters, and sticking out to the side of the railcar. This railcar was then propelled along a rail track where the impactor would hit the pole, standing alongside the track. At impact, a velocity of approximately 128 km/hr was achieved. The full scale test results were limited to photo’s (Fig. 1), which showed the failure mode of the particular structure (a glass fibre tube with integrated couplings), and indicated the damage to the wing.

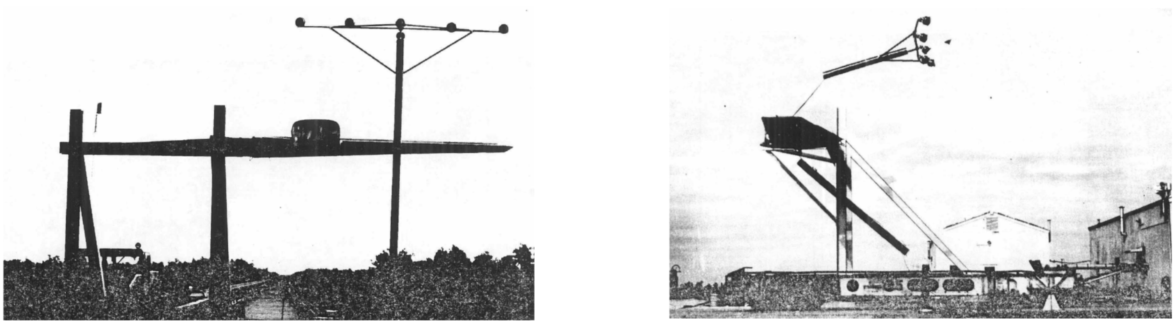

Fig. 1 Light aircraft wing mounted on a railcar, hitting a frangible approach light mast, [3]

A successful failure mode was achieved for these poles (the structure breaking up in pieces), which has the advantage that the mass accelerated during the impact is limited. A further important observation was the undesirable effect that electric cables may have on the failure mode, (hence the importance to incorporate these in a frangible structure when testing). The level of frangibility of the mast was determined by considering the damage to the wing. The damage consisted of a slot of about 25 cm wide that extended from the leading edge of the wing back to the centre wing spar, which was considered “minimal damage” (Fig. 2).

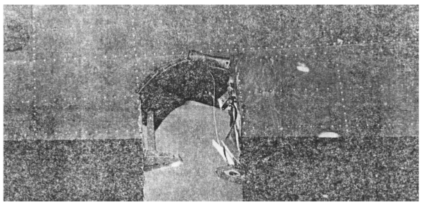

Fig. 2 Damage to a light wing after the collision [3]

Fig. 3 Piper Navajo PA 31, max. take-off weight 2950 kg

Further technical data for this particular mast design were obtained with static drop tests on a single frangible coupling, carried out in a laboratory. This is a typical procedure for testing individual frangible couplings for small poles, but not sufficient to characterize full scale impact events of this magnitude.

At the first meeting of the FASG, tentative frangibility requirements were formulated, for which a representative impact scenario was defined. The group recognized that the aeroplane mass to be considered for frangibility design should be sufficiently low to protect the bulk of light aeroplanes, but not too low to affect the capability of the structure to withstand the environmental loads. Ultimately, the group agreed to use the following parameters in its further work:

- minimum aeroplane mass under which a frangibly designed object should fail when impacted: 2500 kg;
- impact speed to be used in the design of aids that would be impacted by ground borne aeroplanes 50 km/hr;
- impact speed to be used in the design of aids that would be impacted by airborne aeroplanes 140 km/hr.

The velocities chosen are typical for such light aircraft, when close to any of the objects considered.

At the third meeting of the FASG in 1990, the group agreed to revise the minimum aeroplane mass upward to 3000 kg. This revision reflected “work in the US, aimed at protecting aeroplanes heavier than the Piper Navajo (model PA-31-325) with a maximum take-off mass of around 3000 kg”. The investigation had indicated that aids could be designed to break, distort or yield when impacted by such an aeroplane, and at the same time be sufficiently rigid to withstand the wind and ice loads, as well as jet blasts. (Most likely, the work referred to is the work reported in [3]). Hence, the design guidance material [4] as it exists today, states in section 3.3.2 that

> *“a frangible structure should be designed to withstand the static and operational wind or jet blast loads with a suitable factor of safety but should break, distort or yield readily when subjected to the sudden collision forces of a 3000-kg aircraft airborne and travelling at 140 km/h (75 kt) or moving on the ground at 50 km/h (27 kt).”*

At the fifth meeting of the FASG in 1998, it was remarked that this impact scenario may be relevant for most frangible structures near runways at airports, but not for the ILS glide path antenna. It was considered questionable whether design criteria associated with a 3000 kg aeroplane could be applied to the tower structure supporting the ILS glide path antenna. The mass of the antenna itself is typically 60 – 80 kg, and the tower, which could be up to 18 to 20 meters high, is often stabilised by supporting wires.

At the last meeting of the FASG in 2003, it was also doubted that full scale tests on such large structures would be undertaken, to allow a deviation of this point of view. Hence, in the current design guidance material [4], which is the result of the work of the FASG, it is stated in section 4.9.31.b that

> *"considering the unique nature of the tower structure supporting the ILS glide path antenna, frangibility criteria have not yet been developed."*

3. Design Concepts

With frangibility requirements defined, and with the insight acquired meanwhile that frangible structures need to be lightweight and fail upon impact in a predetermined, benevolent failure mode, several efforts were undertaken to test new and existing, frangible support structures for approach lighting systems. As numerical methods to simulate the complex failure behaviour of impacted structures were not available at the time, development by trial and error was foreseen.

At the second meeting of the FASG in 1986, the results of a first, full scale test campaign, carried out by the Swedish Board of Civil Aviation [5] on an adapted commercial tower concept, were presented. This design concept consists of a tripod of small diameter aluminium tubes, held together by clips which disconnect upon impact, thereby reducing the moment of inertia of the tower and inducing its collapse. It is a very light structure, intended to carry just one light.

Fig. 4 Swedish design concept built up from small diameter aluminium tubes, [5, 8]

At the third meeting of the FASG in 1990, results of a full scale test campaign, carried out by the Finnish company Exel, were presented [6]. The design concept entails a lattice structure built up from four vertical members, connected by diagonal cross members. All elements of the tower consist of small diameter fibreglass/epoxy tubes, with the diagonal members inserted in the vertical members, and fixed by bonding. Upon impact, the bonding breaks, and the tower collapses into individual tubes. The structure may carry a cross member at the top, holding five PAR56 lights.

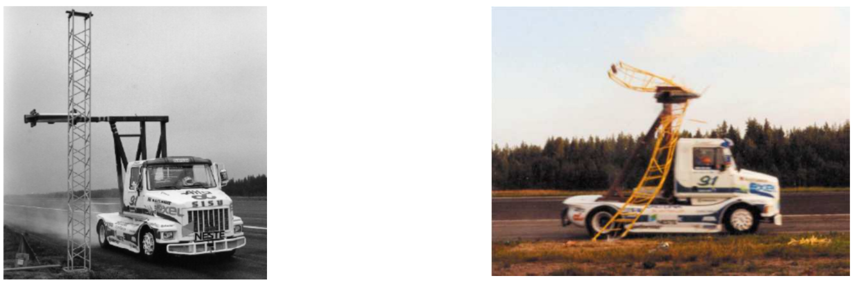

Fig. 5 Finnish design concept built up from small diameter fibreglass/epoxy tubes [6, 9]

At the same meeting of the FASG, results were presented of a test campaign carried out on a design concept developed by the National Aerospace Laboratory (NLR) in the Netherlands [7]. The design concept consists of a frame structure, using similar large diameter glass/epoxy tubes and similar integrated frangible couplings as used for the approach light structure developed for the FAA in 1979 [3]. However, rather than a single pole, it was built up as a four-legged frame, in order to carry five large 6.5 kg lights that were mandated at the time by the Dutch aviation authorities for Schiphol Airport, rather than the common, 1.5 kg lights used elsewhere. Due to its size, only one leg was tested, horizontally. It was tested with a wing impactor that unfortunately collapsed inwards due to insufficient side support. After modification, it would become the ***standard wing impactor*** in subsequent test programmes.

Fig. 6 Dutch design concept built up from large diameter fibreglass/epoxy tubes, test configuration and wing impactor [7]

At the fourth meeting in 1996, more full scale test results were presented for the Swedish [8] and the Finnish design concepts [9], this time with the standard wing impactor as discussed above.

At the fifth meeting of the FASG in 1998, results of a full scale test campaign, carried out by the Norwegian company Juralco, were presented [10]. The design concept entails a lattice structure with three legs and diagonal members, each side consisting of two legs with integrated diagonals, made from one aluminium extrusion. Taller structures are built up vertically from different sections on top of each other, connected with frangible joints. Upon impact, the tower collapses by buckling of the structure, and separation at the frangible joints.

Fig. 7 Design concept built up from aluminium lattice sections [10]

At the same meeting of the FASG, results were presented [11, 12] of two full scale test campaigns carried out on a design concept developed by Millard in Canada, using the standard wing impactor during the second campaign. The design concept entails a lattice aluminium structure with three legs and diagonal members. The structure is built up vertically from two different sections. Upon impact, the structure buckles at the impact point and at the base, after which the tower rotates out of the way.

Fig. 8 Design concept built up from aluminium lattice sections [11, 12]

In later years, another design concept for ALS supports was developed and tested independently by two companies, consisting of a single large diameter fibreglass/polymer hollow tube, without integrated couplings but with frangible connections at the base. The test results were not available to the FASG at the time when the ICAO documentation on frangibility was concluded.

4. Full Scale Testing Procedure

Until the third meeting, it was thought that tests to determine frangibility could be limited to detail tests on frangible couplings or integral breakaway mechanisms in the laboratory, as described in the US study of 1979 [3]. Limits for the frangibility parameters of such couplings were proposed on the basis of these lab tests, including a limit for the contact time needed to break the coupling. From the results of the first new full scale tests, presented by EXEL at this meeting, it was concluded that "it was doubtful if the results obtained by testing a segment of a structure would be representative of the behaviour of the structure as a whole". Hence, the group agreed that the procedures established to substantiate frangibility should envisage full scale tests, not component tests. A typical full scale test configuration, proposed by Sweden at the time, is shown in Fig. 9.

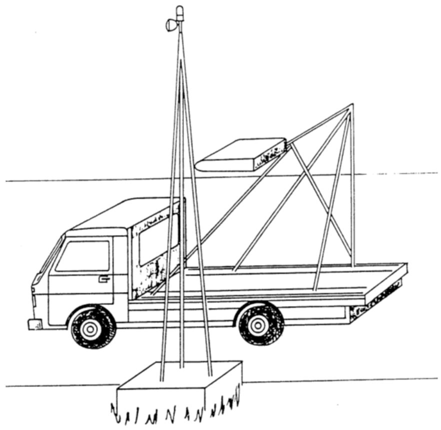

Fig. 9 Full scale test configuration proposed for frangibility testing

Furthermore, for the aids that would be impacted by airborne aeroplanes, it was considered evident that more experimental work needed to be undertaken, before the amount of energy that the reference aeroplane could be allowed to dissipate, could be established. To this end, the study group agreed that a standard wing section should always be used for the tests as an impactor, and that there was no need to develop an aluminium tube for this purpose, as suggested earlier. The principal reason for this conclusion was that it would be difficult to estimate the damage likely to be caused to the wing of a reference aeroplane from the damage caused to such an aluminium tube.

An improved version of the wing impactor as used by NLR [7], with improved side supports, was agreed upon as a standard wing impactor for future testing. It was used subsequently for testing Finnish, Swedish, Norwegian and Canadian masts. This impactor was derived from the dimensions of the wing of the Beechcraft Model 80 Queen Air, which was in the NLR inventory at the time, an aeroplane similar to the Piper Navajo. The standard wing impactor is fully described in NLR Report CR 92153L [13]. A first sketch of this impactor was incorporated in the report of the third meeting of the FASG (Fig. 10). This sketch also shows that the aluminium wing section is connected to a square steel tube. This tube is to be connected via two load cells to the frame mounted on the truck. With these load cells, the force-time history is recorded, as well as the duration of the impact.

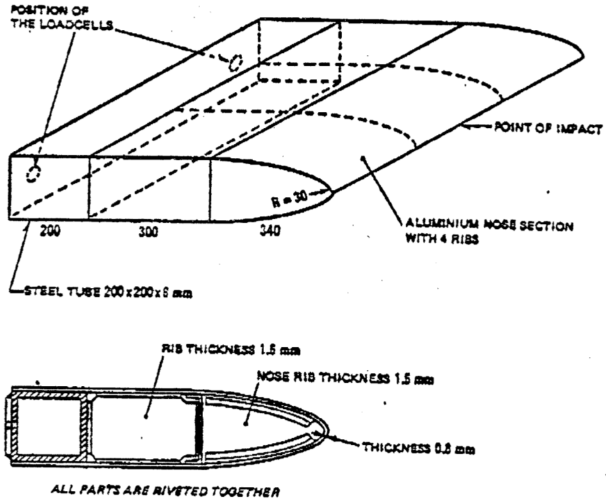

Fig. 10 Standard wing impactor for frangibility testing

At the third meeting, an additional test parameter was defined. The high speed impact test was envisioned for objects having an overall height in excess of 1 m (1.2 m in [4]), and located in positions where they are likely to be impacted by an aircraft in flight. So it was proposed to mount the impactor on the frame of the vehicle, so that the object will be struck at a point approximately (at least) 4 m above ground level, or (at most) 1 m below the top of the object, whichever is higher.

ALS structures may be much taller than 6 m. For that reason, frangibility is required for the top 12 m of ALS towers. Frangibility testing by impacting 1 m below the top might mean testing at 11 m height. During the timeframe the FASG was active, only Juralco has tested masts taller than 6 m, but not 1 m below the top, see Fig. 7.

It was noted at the third meeting that “the design test be carried out in such a manner that the conditions, under which the aid might actually be impacted, are simulated as closely as possible”. This was incorporated in [4] section 5.2.8 as follows:

> *“The conditions under which the structure might actually be impacted are simulated on a worst-case basis. To this end, tests should be conducted with a vehicle-driven impactor with a representative mass equivalent to the weight of the intended aid mounted on the top of the tower”.*

To obtain a proper view of the failure mode, including the effect of flying debris, it is stated in [4] that the impact should be recorded by a high-speed camera so as to reveal the mode of failure.

The pass/fail criterion for the frangibility of a structure is based on the extent of the damage to the wing. Skin damage is acceptable, but the front spar, which is part of the load carrying structure of the wing, must survive, as shown for example in Fig. 11.

Fig. 11 Typical impact damage on the standard wing impactor

In addition to recording the force-time history on the wing, and obtaining high speed footage, the velocity of the vehicle has to be measured, for instance by radar, or from the rotational speed of the drive axle of the truck. From the full scale test results it was learned that the impact of a lightweight wing section on a lightweight frangible structure hardly influences the speed of the truck. For further processing of the data, the velocity is therefore generally assumed to be constant. In this manner, the force-time history (Fig. 12) can be developed into a force-displacement curve, and the energy absorbed by the wing (Fig. 13) can be determined.

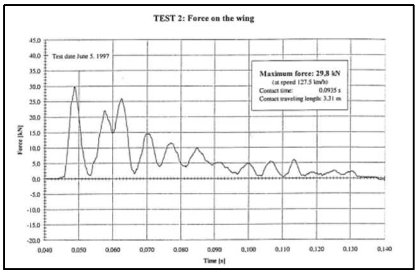

Fig. 12 Typical force-time history

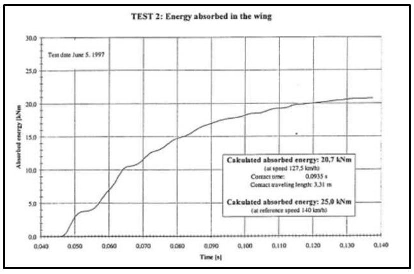

Fig. 13 Typical absorbed impact energy

5. Design Criteria and Test Parameters

The FASG defined design criteria for dedicated frangible couplings right from the start. However, defining design criteria for complete structures became possible only after collecting full scale test results for a variety of structures. It took a long time before these test results were obtained. The reasons for this long period were the dependence on the investment of new players to enter the market for frangible approach light structures (Exel, Juralco), and the necessary contributions of national airworthiness authorities to finance test campaigns on existing products (Swedish, Canadian) or experimental developments (Dutch).

At the fifth meeting of the FASG in 1998, test data of all available full scale tests were summarised. The first tests, contributing data for the FASG, were carried out in 1984 (Swedish design), and the last tests were carried out in 1998 (Canadian design). Tests results were now available from five different sources (Sweden, Finland, Norway, the Netherlands and Canada). Results for structures made of aluminium and of composite materials were available, and results were available for structures of different structural concepts: lattice structures, single poles and tripods.

The design criteria originally proposed for individual frangible couplings were the maximum force exerted on the coupling, the energy to break the coupling, and the duration of the breakage of the coupling in a low velocity impact test. In contrast, the test data obtained with the full scale tests are the force-time history of the force exerted on the wing during the impact, and the wing velocity needed to compute the energy absorbed by the wing. Hence, the maximum peak force on the wing, and the maximum energy absorbed by the wing as the result from an impact with a structure, were proposed as the critical design criteria for the frangibility of this structure. A limitation of the impact duration was not considered discriminating, as the duration is largely governed by the impact height and the velocity of the wing impactor. Instead it is required that the tower does not wrap around and remain in contact with the aeroplane for a long time after the impact.

For all impact test results available at the fifth FASG-meeting (Table 1), these parameters were plotted in one graph (Fig. 14). Not all data points represent tests at 140 km/hr; several tests were carried out at lower speeds. Also, some tests included cables and top masses, others didn’t.

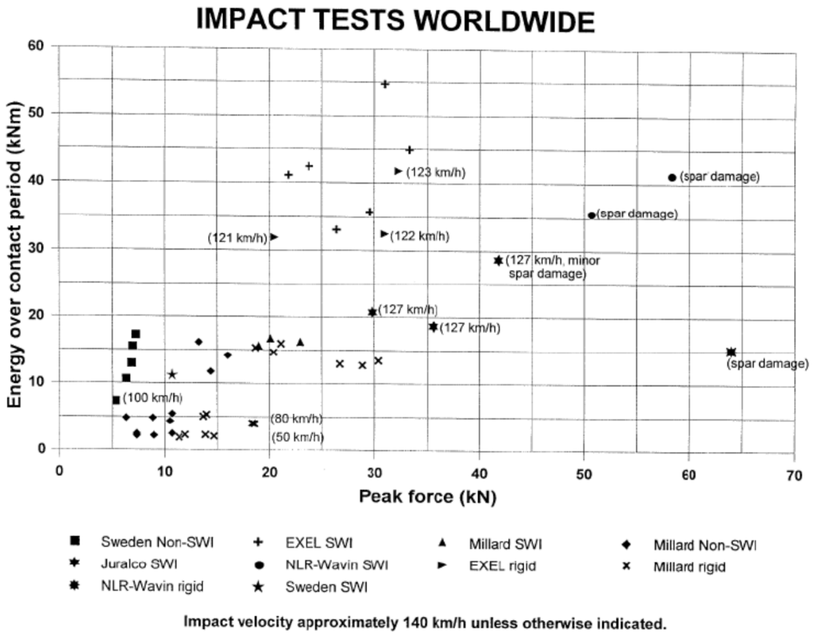

Fig. 14 Graph of all data points for energy absorbed by wing, versus peak force

Table 1. Overview of tests which contributed to the frangibility criteria

Year	Ref.	Nation	Design concept	Impactor(s) based on aircraft type	Number of tests
1984	5	Sweden	Aluminium tripod, 3 legs	Piper Cherokee PA-28 based, non-standard wing impactor: 1 m wide, 2 ribs spaced at about 650 mm; skin 0.7 mm	5
1990	6	Finland	Fibre glass lattice, 4 legs	Rigid: steel tube d = 50 mmm	3
1989	7	Netherlands	Fibre glass tube frame structure, 4 legs	Rigid, steel tube d = 200 mm Queen Air Model 80 based, **pre-standard wing impactor:** 4 ribs spaced at 325/350 mm; skin 0.8 mm	1 2

Year	Ref.	Nation	Design concept	Impactor(s) based on aircraft type	Number of tests
1991	9	Finland	Fibre glass lattice, 4 legs	**Standard wing impactor**	6
1997	10	Norway	Aluminium lattice, 3 legs	**Standard wing impactor**	4
1997	11	Canada	Aluminium lattice, 3 legs	Rigid, half steel tube, D = 305 mm Piper Aztec PA-23-250F based, non-standard wing impactor: 5 ribs spaced at 280/305 mm; skin 0.5 mm	12 14
1998	12	Canada	Aluminium lattice, 3 legs	**Standard wing impactor**	5

Bounds were drawn around the data points representing impacts that left the wing in a survivable state (Fig. 15). In this manner, design criteria for frangibility were defined as a maximum allowable peak force of 45 kN, and a maximum absorbed energy of 55 kNm.

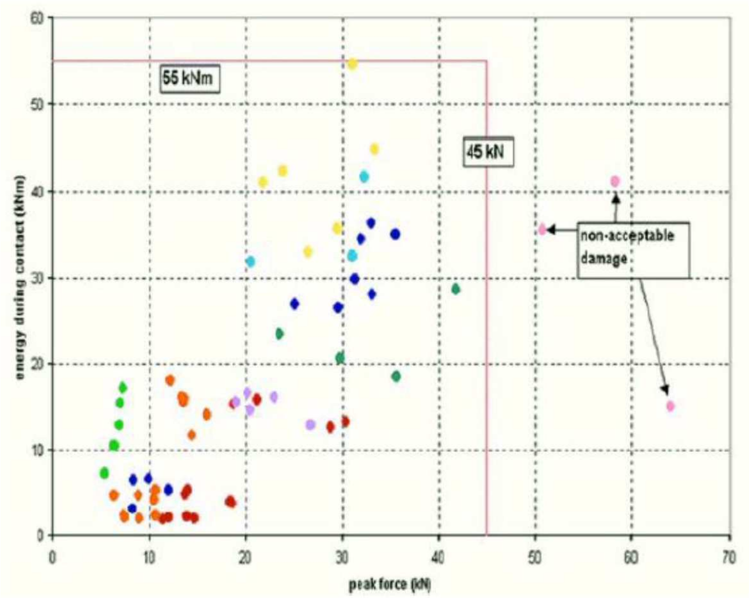

Fig. 15 Frangibility criteria for energy absorbed by wing and peak force

At the sixth meeting, a CD was made available, assembled by NLR, containing footage of the full scale tests that are discussed above [14].

Comparing the Canadian test results, it was concluded that a more rigid impactor will lead to a higher peak force and a shorter contact period, but will hardly affect the energy over the contact period and the mode of failure, see Fig 16. These results were taken from test campaign I [11], using a wing impactor based on the Piper Aztec PA-23 (max. take-off weight 2360 kg), and from test campaign II [12], using a standard wing impactor.

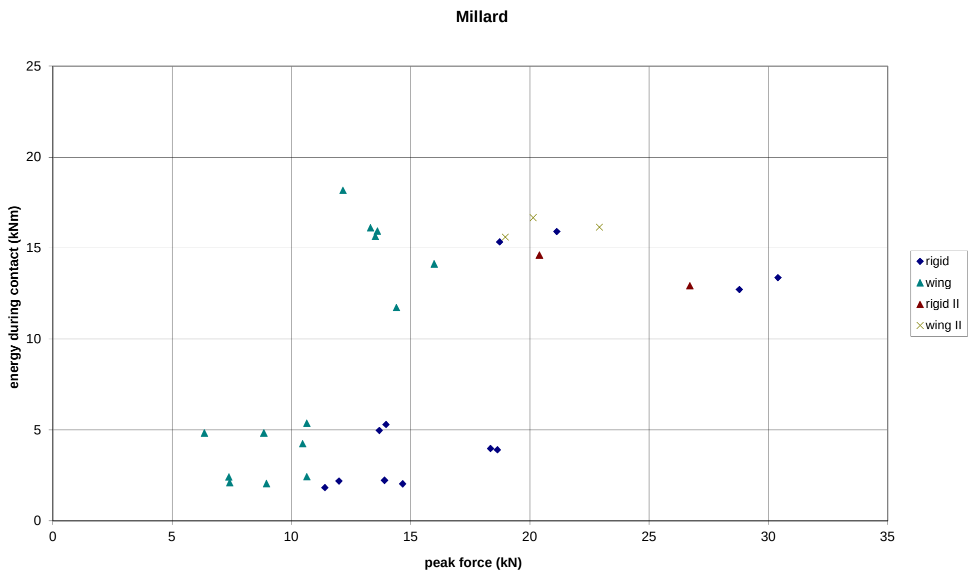

Fig. 16 Canadian test results [11], [12]

The study group therefore revisited the need to use a soft impactor when verifying through test that the frangibility requirement is met. The use of a rigid impactor would not allow the evaluation of the damage to a wing-impactor. However, the use of rigid impactors would be less expensive and would eliminate the effect of any wing deflection and any other variables introduced by a soft impactor that could not easily be controlled. As a result of this conclusion, it is stated in [4], paragraph 5.2.11, that *the recommended impactor design is a “rigid” semi-circular tube*.

It must be pointed out that this conclusion was drawn from the results of a test campaign on aluminium lattice structures. Comments have been received meanwhile, that the use of rigid impactors may change the failure mode of towers consisting of a single large diameter fibreglass/polymer hollow tube, without integrated couplings. Rigid impactors may slice through such poles, while soft wing impactors would not. Hence, the results obtained with rigid impactors might not always be conservative.

The other test parameters were maintained, and are incorporated in the design manual [4], paragraph 5.2.14 (test velocity, impact height, requirement to mount a representative mass on the top of the tower and the requirement for wiring and cabling to be mounted and secured).

6. Numerical Analysis

With time passing, numerical analysis methods became available to simulate high speed impacts. At the fifth FASG-meeting in 1998, results were presented of the first efforts to develop a numerical simulation method for the impact of frangible structures by NLR (the Netherlands) and NRC (National Research Council of Canada), advisors to the airworthiness authorities of these countries. NLR used the KRASH-code [15], an explicit code, and NRC at that time used PATRAN/NASTRAN, an implicit code.

The group concluded that a Chapter 6 *Numerical Simulation Methods for Evaluating Frangibility* of the design manual [4] needed to be developed. Hereto, the further development of the two computer models for simulation of impact scenarios was planned, and a final meeting was foreseen to define the contents of Chapter 6, as well as the wrapping up of a few other items.

At the sixth meeting in 2003, results of numerical results were discussed. NRC now had used an explicit finite element code, LS-DYNA3D, and NLR still used its hybrid code KRASH. A finite element code uses many degrees of freedom, and requires sophisticated material models to reproduce the complex post failure properties. This is a challenge particularly for fibre reinforced plastics, less so for aluminium. The hybrid code is based on structural elements, requires considerably fewer degrees of freedom, and requires structural properties, which can be derived from tests on structural components, rather than material properties. Both methods were shown to produce satisfactory results, in comparison with the test results. As a result, NLR and NRC were asked to develop Chapter 6 of the design manual to completion. This was done, and the material was incorporated in the design manual [4] that appeared in 2006.

The analysis work was first published in the International Airport Review, Issue 1, 2001 [16], also available as NLR TP 2001-064 (with a correct reference list). In this publication, the following simulation results were shown:

Fig. 16 KRASH results (failure mode and energy plot versus test result)

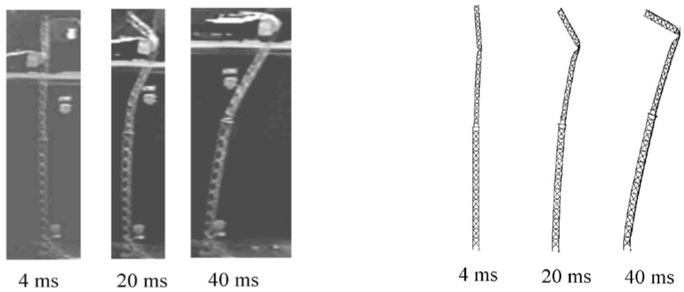

Fig. 17 LS-DYNA3D results (failure mode versus test result)

It was recognised that nonlinear numerical analysis, of structures deforming beyond first failure, is dependent on the right application of a whole range of parameters. Extreme structural distortion occurs, complex contact conditions exist between multiple components, large impact deformation occurs, and sophisticated material modes are needed. In that sense it was judged that, although post-test analyses were shown to be successful, it is important to obtain confidence in the parameters chosen for a particular design, by validation of the model with high velocity test results. Validation criteria for the numerical simulation methods are the deformation mode, the location and timing of failure, the impact force and the energy absorption. The limitations for the justified use of numerical models and methods to assess frangibility have been formulated in [4], section 6.2.1 as:

Once verified, these models can be used to investigate other configurations and parameters of impact to assess the performance of the structure. The models can also be used to interpolate test data for new or varied conditions, and to extrapolate it over a short range to help predict the *behaviour and performance of the structures. The ultimate goal is to be able to develop the capability and confidence to model new and different situations and structures through analysis (alone). However, this goal is not likely to become available in the near future, although the initial goal of interpolation and minor extrapolation is viable.*

8. Conclusions

Over the last decades, frangibility requirements, criteria, design guidelines and test methods were developed, by the Frangible Aids Study Group (FASG) under guidance of the ICAO, for many aids and their supporting structures at airports. The process followed to develop this material is described in the present paper.

The work of the FASG has resulted in an updated Annex 14 “Aerodromes”, with improved specifications for frangibility, and a newly created Part 6 “Frangibility” of the ICAO Aerodrome Design Manual in 2006. The work of the FASG was discussed in the ICAO journal of 2003 [17], Airport Technology of 2005 [18] and in Aviation Safety World of 2006 [19].

Frangibility regulation for ILS glide slope towers has as yet not been developed, due to the sheer size of these towers. The present overview may be useful for the development of requirements, criteria, design guidelines and test methods for the frangibility of other structures at airports.

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