NTNU
Det skapende universitet

Konseptutvikling av frangible flyplass master

Thomas Angell Storhaug

Master i produktutvikling og produksjon
Innlevert: juni 2014
Hovedveileder: Terje Rølvåg, IPM

Norges teknisk-naturvitenskapelige universitet
Institutt for produktutvikling og materialer

Abstract

Frangible aviation masts are designed to safeguard lives, and as such is an important field of scientific research. Testing a mast for frangibility encompasses complex fields of science, and the transient dynamic analysis' done by numerical simulation are time consuming and complex. Doing research in this field has got a lot of potential, and coupling this with the rapid evolution of computing power, the possibilities in numerical simulations are huge. Finite element analysis is a very powerful tool used to simulate complex static and dynamic problems, and this is what has the potential to overtake actual physical testing in the future.

Table of Contents

Abstract 1

Table of Contents 2

Introduction 3

Summary 4

Documentation 5

- **Crash safety requirements for aviation masts** 5
- **Types of aviation masts and designs by vendors** 7
  - Elevated runway and taxiway edge lights 7
  - Taxiing guidance signs 7
  - Precision approach path indicator (PAPI) and Visual Approach Slope Indicator System (VASIS) 7
  - Wind direction indicators/ transmissometers/ forward-scatter meters 8
  - ILS/MLS structures 8
  - Approach lighting systems 8
- **Masts by vendors** 9

Testing for frangibility 10

- **Physical testing for frangibility** 10
  - Test procedures 11
  - Acceptance/rejection criteria 11
- **Reference impactor** 11
- **Impactors used in crash tests** 13
  - Milliard Towers 13
  - Exel aviation masts 14

Creating a Finite Element Analysis model of a crash test 17

- **Creating a representative model of the mast** 18
- **Choosing a reference impactor that fulfils its role** 18

References 26

Introduction

Aviation as an industry is in many circumstances synonymous with a very strict safety regime. There are numerous standards and regulations that minimise the severity in the outcomes of potential accidents, both for airplanes and areas they interact with; namely aerodromes. The standards for which apply to the latter are given by regional and national aviation authorities (NAA). To ensure that regulations and practices of the different NAAs are at the highest degree of uniformity an international agency exists under the banner of the United Nations; the International Civil Aviation Organization (ICAO). All NAA regulations and standards of the 191 agreeing member states of ICAO are developed based on ICAOs own standards.

Summary

In this thesis I study documentation on the frangibility of aviation masts with regards to requirements and documentation on how these masts are tested to evaluate if they meet the requirements. ICAOs requirements are clear in some manner, but are lacking in detail and open to further refinement.

A big subject of the thesis is proposing strategies for creating a finite element analysis model to be used as a tool to evaluate a masts' frangibility. The strategies proposed base on two fundamental philosophies; either basing the model on the recommendations for physical tests, or basing it on the scenario of an airplane crashing into a mast. As I will discuss, it is possible to arrive at an intermediate scenario where the model strives to be as representative of a crash as possible while also relying on assumptions to simplify the model. This model is represented at the end of the thesis.

I also discuss the different strategic propositions with strengths and weaknesses, and arrive at no conclusion as to what's the best strategy. As is often the case in engineering predictions are hard to make, and the best option usually is to test and document theories. This is also the case with the strategies I propose, they may sound reasonable and logical, but unforeseen problems or weaknesses in software might inhibit them from being implemented correctly.

Documentation

Crash safety requirements for aviation masts

For standards and recommendations regarding frangible objects in aerodromes I will be referring to ICAO's "ICAO Aerodrome Design Manual – Part 6 – Frangibility" whose material is closely associated with the specifications contained in ICAO's "Annex 14 – *Aerodromes*, Volume I – *Aerodrome Design and Operations".* It should be mentioned that the different objects and structures that are required to be frangible have also got several environmental service conditions that require a certain strength and rigidity. These are conflicting sets of requirements, one set requires the object to break or deform – the other requires it to withstand its load. I will however not touch upon the requirements toward withstanding loads from environmental service conditions, but will solely focus on the frangibility aspect of design.

The design manual defines 17 objects that have to be located in the operational area of an aerodrome and hence requires a frangible design;

- Elevated runway, taxiway and stopway lights
- Approach lighting systems
- Visual approach slope indicator systems
- Signs and markers
- Wind direction indicators
- Instrument landing system (ILS) localizer equipment
- ILS glide path equipment
- ILS monitoring antenna
- Microwave landing system (MLS) approach azimuth equipment
- MLS approach elevation equipment
- MLS monitoring antenna
- Radar reflectors
- Anemometers
- Ceilometers
- Transmissometers
- Forward-scatter meters
- Fencing

Annex 14 – *Aerodromes,* Volume I – *Aerodrome Design and Operations,* Chapter 5 defines the circumstances for when these structures should be frangible;

"

- where the height of a supporting structure exceeds 12 m, the frangibility requirement should apply to the top 12 m only; and

- where a supporting structure is surrounded by non-frangible objects, only that part of the structure that extends above the surrounding objects should

be frangible.
“

The annex also describes locations and areas where any structure that extends above the ground must be frangible, but as this is a study on masts that have the frangibility requirement it is assumed that these masts are located in any of these areas.

Frangibility is the ability to distort in such a way that the object in question does not pose any danger of damaging or otherwise act in a hazardous way towards whatever impacted the object. Being a frangible aviation mast means the mast is in danger of being hit by an aircraft, either on the ground or in flight. The obvious reason for requiring these masts then to be frangible is to safeguard the lives of the passengers and personnel in any aircraft that might hit one or more of these masts.

A mast may impact the aircraft in three ways during a crash:

1. The aircraft may lose momentum from the impact.

The velocity of the aircraft is governed mathematically by the integral of the force it’s exposed to, over time. This means that the duration of contact between the aircraft and the mast, while the mast is still imposing a force on the aircraft, should be minimal, as well as the force being minimal. As a note, one procedural requirement for a crash test of a frangible aviation mast is that the velocity of the reference impactor should be kept constant. If the requirement would instead be to measure the loss of momentum, and use this as a basis for energy calculation, the tests accuracy would suffer because the velocity of the vehicle carrying the impactor would also affected by friction, both from the ground and from aerodynamic drag, and these forces are difficult to measure and take into consideration when calculating the change in kinetic energy.

2. The aircraft may change direction.

There’s not much to comment on this point with regards to measurable values; the force imposed on the aircraft by the mast should be minimal. However this point relates to the visual study of a crash test. If a mast entangles the aircraft and imposes forces on the aircraft’s wing after the initial impact by leaving some mass on the wing, it might force the aircrafts direction.

3. The aircraft may suffer structural damage.

This is directly related to the energy the mast imposes on the aircraft. The longer the aircraft is exposed to a force the bigger the deformations will be, i.e. the higher the energy a mast impose on an aircraft the more the impacted part of the aircraft will deform.

The mast will impose energy on the aircraft in accordance with the frangible mechanisms it is designed with. If the mast is designed to break into parts it will impose on the aircraft the required energy activating these breakaway mechanisms. Likewise if it’s designed to deform plastically or elastically, the energy required to deform the mast is imposed on the aircraft. If the mast, or part of the mast, attaches to the aircraft for some time after the impact it will also impose on the aircraft the energy required to accelerate the mast or that part to the aircrafts velocity.

As is known the stress related to a force is also relative to the area on which the force is induced: the bigger the area the smaller the stresses. The geometry of the mast is therefore also an important factor with regards to the deformation the aircraft will experience upon impact.

A structure that’s frangible may feature different mechanisms and concepts that make it frangible. The structure may be designed modularly where the connections between its modules constitutes its frangibility by being very brittle, or the material of the structure itself yields or breaks when impacted. The structures can of course include several types of frangible concepts.

The frangible concepts should activate requiring as little force and energy as possible, while not imposing, or as little as possible, on the masts ability to withstand the environmental loads its exposed to.

Types of aviation masts and designs by vendors

The different types of structures that should be frangible may be arranged into groups with regards to their size. In this report I’m mostly interested in approach lighting system masts, but I will mention the different groups and their frangibility requirements.

Elevated runway and taxiway edge lights

These objects are light fixtures elevated slightly from the ground. The frangibility criteria for these structures is a simple yield criteria; each fixture should have a yield point no more than 38 mm above the ground which should withstand a bending moment of 204 J without failure, but should separate from its base before the moment reaches 678 J.

Taxiing guidance signs

From ICAOs *Aerodrome Design Manual – part 6 – frangibility*, chapter 4.9.5

“

Signs should be frangible. The overall mass of a sign including mounting fixture should be limited to 24.5 kg/m length and the total length of a sign should not exceed 3 m.

Mounting legs for each sign should have frangible points located 50 mm or less above the concrete pad or stake.
“

Precision approach path indicator (PAPI) and Visual Approach Slope Indicator System (VASIS)

These are lights that will be in the immediate vicinity of landing aircraft and will therefore be exposed to extreme wind loads. In ICAOs *Aerodrome Design Manual – part 6 – frangibility* it is recommended that the structures be mounted with a minimum of three adjustable mounting legs. The mounting legs should be frangible with a breakaway mechanism.

Wind direction indicators/ transmissometers/ forward-scatter meters

These structures are of similar design as approach lighting systems and are therefore required to meet the same criteria as approach lighting systems.

ILS/MLS structures

There are several different structures associated with ILS and MLS equipment. Some of the objects, like the ILS localizer, can be mounted on lightweight towers and should therefore meet the frangible requirements of approach lighting masts. However, objects like the transmitter housing for ILS installations, the MLS azimuth antenna and the MLS elevation antenna are objects that cannot be mounted on lightweight structures, and there have not been developed frangibility requirements for such structures.

Approach lighting systems

Figure 1; Approach lighting structures (Frangible Composites)

Approach lighting systems are systems of light fixtures designed to aid landing aircrafts approaching the airfield. These light fixtures are situated on the centre line of the runway and are prone to impacts with airplanes out of course. The masts holding the light fixtures are required to be positioned in such a way that the fixtures are at certain heights from the ground, and consistent relative to each other. This means the masts may be very tall depending on the slope of the ground, hence the need for specific frangible requirements for these masts.

The design criteria devised by ICAO are developed with small aircrafts in mind: airplanes with a total mass of 3000 kg. As the approach lighting masts may be very tall, >12 m high, the mast should be frangible for such an aircraft at 140 km/h, as it is assumed that the mast may be impacted in flight. For this circumstance the mast should not impose a force exceeding 45 kN, nor should the energy transferred from the mast to the aircraft be greater than 55 kJ. The mast should also be designed to not entangle the aircraft after impact. Any wiring and cabling needed for the lights during operation, as well as the light fixtures themselves, are integral parts of the structure and must be considered when designing towards frangibility. The energy transferred to the aircraft is calculated by integration of the impact force with respect to distance.

Even though the criterion with regard to force is very definite, it leaves room for interpretation. By studying different graphs showing force relative to duration of impact, as I will be showing later, the graphs may have very high peaks (large force) that last for a very short amount of time. As have been discussed earlier the duration the impacted airplane is exposed to a force has a big impact on how much the airplane deforms or its velocity and direction is changed. This leaves these peak forces open to filtering when studied after testing, and rightfully so: if a force lasts for a few milliseconds it won't have a large impact on the airplanes trajectory or velocity, neither will it impose large deformations on it. For this reason one could argue that filtering out the highest peaks to smooth out the force curve is justified. There is however no mention of using techniques like these to interpret the results in physical tests in ICAOs design manual, which opens up the possibility of generating results to accommodate the design criteria by using different methods of interpretation on different types of masts.

Thomas Storhaug 15.6.14 18:07
Comment: Referanser!

Masts by vendors

Vendor	Lattix	Exel	Pollite	Frangible composites	Milliard Towers
Mast type	Lattice towers	Lattice towers	Poles	Poles and lattice towers	Lattice towers
Material	Aluminium	Fibreglass composites	Fibreglass composites	Fibreglass composites	Aluminium

The table shows a slight overview of the masts that are available for approach lighting systems. As the vendors are interested in selling their masts they are all advertising the fact that they are accepted under ICAO regulations. However, I have only been able to get a hold of documentation of the evaluation process from three of the vendors, Lattix[7], Exel[6] and Milliard[2-5]. The studies in the next sections will refer to these tests and their reports in different sections.

The report of the finite element analysis of Lattix' masts conclude with the mast not meeting the requirements of ICAO. This report does only do a finite element analysis of the mast, and does not compare the results from this test to any physical test. I know that such a physical test have taken place[12] but I have been unable to get a hold of any documentation or report from it.

Testing for frangibility

Now that I have established the standards and criteria that must be fulfilled by a structure for it to be frangible, I will study the methods used to test for these criteria. ICAO has devised a set of procedures in guidance of how to perform these tests. As stated earlier the focus of this report is approach lighting masts, so the procedures studied will be for testing approach lighting masts for frangibility. For systems that have the same criteria for frangibility as these masts ICAO recommends proceeding in accordance with the procedures for approach lighting masts.

Physical testing for frangibility

The tests that a virtual simulation will have to be based on are high-speed full-scale tests of a crash between a reference impactor and the mast that is tested. These tests are conducted under as close to operational conditions as possible for the masts with regards to load and wiring. The reference impactor represents a small aeroplane of only 3000 kg as it is assumed that these aircrafts will suffer the most from an impact with a structure. Furthermore, if the former assumption holds true, if a mast is frangible enough to not pose a threat to a small aeroplane it will not pose a threat to larger aircrafts either. The reference impactor is mounted on a vehicle that is able to accelerate to and maintain the speed recommended by ICAO and crashed into the mast at this speed.

Figure 2; Test setup for the Exel test

Test procedures

ICAOs *Aerodrome Design Manual – part 6 – frangibility,* chapter 5 defines the procedures of the test:

- It should be conducted at a speed of 140 km/h
- The point of impact between the impactor and the mast should be 4 m above the ground or 1 m below the top of the structure, whichever is higher
- The mast should be mounted with a mass representing the intended aid on the top of the mast along with all wiring and cabling also mounted and secured
- The impact should be recorded by a high-speed camera to make it possible to visually inspect the failure modes during impact
- Impact speed should remain constant during impact and should be recorded
- The data from the loading cells should be accurately recorded with a recording speed of at least 10 kHz

These points indicate the intent of the test, to simulate a situation where a small airplane crashes with a structure while landing. Since the speed of the impactor is relatively high the sequence of reactions and deformations of the mast have a very short time span despite large deformations. It is therefore emphasised that the method of recording data should take this into account and record data at very small time intervals.

This is an important point to make with regards to an argument towards doing these kinds of tests virtually. In a virtual simulation of a crash test you can dictate the rate at which to calculate the different deformations and reactive forces without having to rely on the accuracy of any equipment.

Acceptance/rejection criteria

The criteria for acceptance and rejection are also found in ICAOs *Aerodrome Design Manual – part 6 – frangibility*:

- The mast is considered frangible if it meets the requirements set by ICAO with regards to force and energy
- Based upon visual inspection of the crash test these criteria should also be used when determining acceptance or rejection:
  - The mast should not impede the aircrafts trajectory by clinging to it or wrapping around the wing after impact
  - If the mast fragments during impact, the mass of these parts and the way they are released should not cause hazard to the aircraft
  - Structures that may only hinder an aircraft on the ground are allowed to do more damage than structures impacted by airborne aircraft

Reference impactor

To test a mast for frangibility requires a setting that can represent a real crash in such a way that the results of the test are indicative of how the mast will impact an airplane in a real crash situation. The mast should be mounted with its intended light fixtures and cables, and the reference impactor should be designed in such a way that it fulfils its role as a representation of a wing segment. To fulfil its role, the reference impactor should be designed in such a way that the results of the test indicates how the tested mast performs with regards to the three ways it can impact an aircraft:

1. The aircraft may lose momentum
2. The aircraft may change direction
3. The aircraft may suffer structural damage

In 1998 the Frangible Aids Study Group of ICAO held a meeting where they analysed the results of several full-scale crash tests on different types of masts[9]. In these crash tests the impactor was designed structurally identical to existing wing section of small airplanes. The impactor measured energy and peak forces, but the deciding factor deeming the masts frangible or not was the damage it had done to the impactor. By analysing these results the FASG-meeting concluded that the masts that had been accepted as frangible where bounded by an impact energy of 55 kJ and a peak force of 45 kN. These tests also showed that by using a large diameter rigid impactor the resulting peak forces were higher. This lead the group to believe that rigid impactors could be used in future tests to save costs.

Figure showing energy and peak forces from tests

ICAO based its recommendations on the results from the FASG-meeting and its note on rigid impactors. The fact that the rigid impactors gave more conservative results with regards to forces creates a safety factor against conditional differences in test equipment and test procedures. Low costs, both related to manufacture as well as the possibility to reuse the impactor, as it experiences negligible damage, is another argument by ICAO for using a rigid impactor. The exact recommendations given by ICAO are as follows:

"…the recommended impactor design is a "rigid" semicircular tube, 1000 mm or five times the maximum cross-sectional dimension of the tower, whichever is greater. The outer diameter of the tube should be approximately 205 mm and the wall thickness should be sufficiently thick to represent a rigid body but no less than 25 mm. The material used for the impactor should be steel. The surface finish should be generally smooth and no coating or finish is required."

Despite the strengths of a rigid impactor there's one area the impactor may fail to give a clear indication of the masts performance; how much damage it inflicts on the wing. The damage it inflicts is as stated not just related to the energy the wing consumes, but also the geometrical design of the mast. A rigid impactor will obviously not experience the same amount of deformations as a real wing section, and may theoretically fail to portray the real frangibility of a mast if the masts geometry is unfavourable with regards to doing damage to a wing.

Another problem that these tests experience is related to the stiffness properties of the entire impactor structure: the impact will induce resonating oscillations in the impactor, which will have an effect on the calculated energy. The load cells in the configuration will, because of their positioning, record these oscillations as contact force fluctuations thereby increasing the duration in which forces affect the impactor. This will in turn increase the calculated energy transfer.

Impactors used in crash tests

There are a few scientific papers documenting crash tests of aviation masts, and the ones I've been able to get a hold of refer to two different tests: a test done on the aluminium lattice aviation towers from Milliard Towers LTD, and the test done on Exels fibreglass composite lattice towers. The reports are scarce in detail concerning the impactors properties and dimensions, but the few details they give, and by studying photos of the tests, a general outline of the impactor can be gathered.

Milliard Towers

Several papers[2-5] refer to the test that was done to this mast, and also compare the results with finite element analysis simulations done on the same type of mast. In the test a semi-cylindrical steel tube is used as the reference impactor. Its dimensions are: 79 cm long, 30.5 cm in diameter and 2.2 cm thick. This steel tube is fixed to a thick aluminium plate which acts as an interface for the load cells. The load cells sit between this plate and an identical plate which is attached to the cantilever beam that reached out of the supporting structure on the driving vehicle. A total of 6 load cells was mounted on the interface, and the total force was calculated as the sum of all these.

Figure 3; test setup for the Milliard test

As a preventive measure in case the tower wrapped around the impactor, a thin 70 cm long steel plate covered the two aluminium plates to avoid the tower getting caught in between the plates.

Exel aviation masts

In 1991 Exel conducted a crash test on their composite lattice mast[6]. This test amounted to part of the reference material that was used to define new recommendations for frangible masts during the FASG-meeting in 1998. As such no standards were developed with regards to the impactor. The impactor used in this test was designed to duplicate a wing section structurally and the evaluation for acceptance or rejection was based on the observed damage the impactor suffered.

Figure 4; test setup for the Exel test

The reference impactor was based on a wing section of a Beech Queen Air aircraft. The frontal part of the impactor, 1000 mm wide, was made up of a wing section, 640 mm deep, made of 2024-T3 aluminium, and a backing column with a square cross section, 200 mm deep. The backing column formed the interface on which the load cells was placed, two in total. To compensate for the fact that the wing section was finite, and that in earlier tests they experienced a unrealistic failure mode of the outer ribs of the wing section, these ribs were supported from the outside.

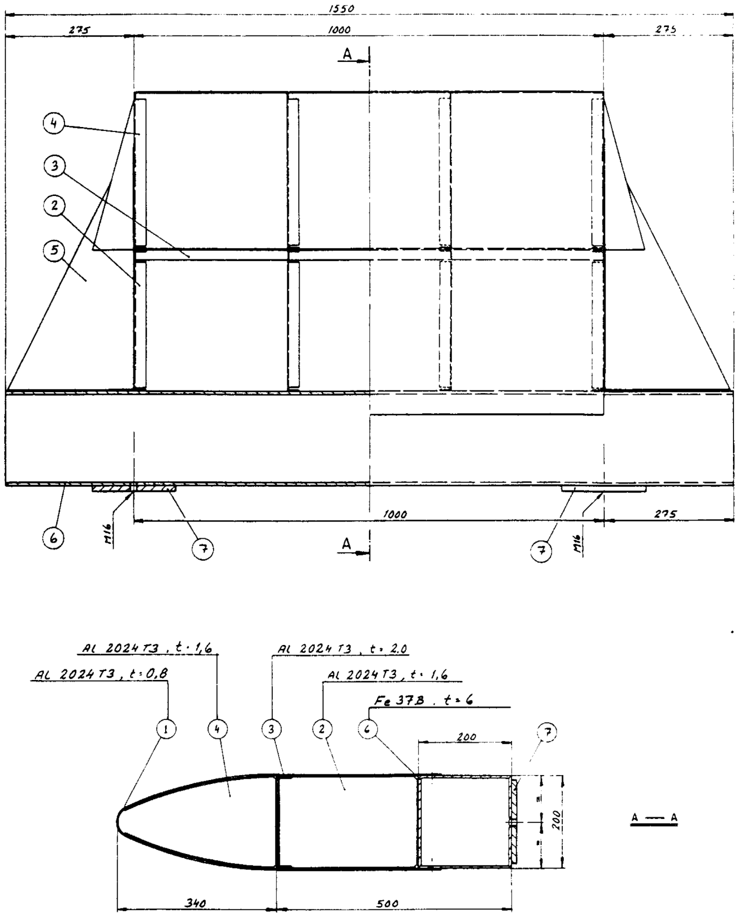

Figure 5; Schematic of the wing section impactor

In their report, the authors comment that earlier attempts with a rigid impactor had induced a different failure mode in the mast, and felt that the wing section type impactor more accurately would predict the outcome of a crash between a wing and a mast. Due to what they refer to as a more brittle failure mode, the rigid impactor was considered more favourable with regards to frangibility than a softer wing structure.

Creating a Finite Element Analysis model of a crash test

The objective of this thesis is to propose different strategies to create a general set of rules for Finite Element Analysis (FEA) simulation of a crash test. If a general set of rules is established and these create a Finite Element model that sufficiently represents a crash between a wing and a frangible mast, it may abolish the need for doing physical tests, and in extent save resources and costs. The costs may be further lowered if the rules are at such a level of detail that the model is very easily created in different types of FEA software. This requires the rules to have as little room for interpretation as possible, which also serve to ensure that the results are reliable for acceptance or rejection of ICAOs requirements for frangibility.

Recommendations for finite element analysis procedures for crash tests have yet to be developed. ICAO recognises the possibilities that this type of numerical simulation offers in their design manual. They acknowledge the need for cost effective methods of testing masts where most if not all combinations of speed, direction, altitude etc. is tested for, which is not realistically feasible with physical tests, and propose numerical simulations as an aid to reach this goal.

To create a reliable finite element analysis model I believe that there are two fundamental philosophies to base upon: create a model that is based on the rigid impactor recommendation given for physical testing, or create a model based on an actual wing crashing into a mast.

Reports from a few finite element analysis simulations of crash tests are available and most of them base their impactor models on the recommendations ICAO give for physical tests. Some of these reports also refer to, and compare against, results from actual physical tests done on the masts they simulate, which gives insight into how well the finite element model represents its physical counterpart. The results are relatively comparable, within a 15-20 % range of the data from the physical tests [2-5]. If the goal of the finite element analysis model is to fully recreate the scenario of a physical test, then these reports build the foundation for such a model.

The power of a finite element analysis gives the ability to model complex structures and also using transient dynamic analysis to predict these structures' behaviour during an impact. This means that theoretically one could model an entire airplane and crash it into a mast. To do this however would take a very long time to both model and simulate as the duration of a numerical simulation depends on the complexity of the model as well as the computers computational capacity. The intent to base a finite element analysis simulation on an actual wing however doesn't require one to model the entire airplane, but to base the models assumptions on an airplane crashing into a mast rather than basing them on a reference impactor crashing into a mast.

The physical tests are based on the scenario where an airplane crashes into a mast at 140 km/h. In their design manual ICAO recommends that the speed in a physical test be held constant, and the impact point should be 4 m above the ground or 1 m below the top mass, whichever is higher. These recommendations are given to limit the cost associated with doing these tests. However these restrictions doesn’t have to be carried over in a finite element analysis. Theoretically a numerical simulation is able to simulate any possible combination of speed and direction, however this is not practically feasible, and a set number of combinations should be chosen to fully predict the outcome of most scenarios of impact.

With regards to the velocity of the impactor it is possible to consider it an initial value in the simulation and then by numerical simulation calculate the loss of momentum the impactor experience from the impact. The resulting change in momentum could then be used in calculating the transferred energy as this would create a change in the kinetic energy of the impactor. Although the constraints related to the physical impactor, frictional forces impeding the impactors momentum, does not exist in a finite element analysis, I recommend defining the velocity of the impactor as constant to be able to compare the results from a FE analysis to a physical crash test.

Creating a representative model of the mast

The mast models main objective is to represent the real mast as truthfully as possible. In earlier[3-5] finite element analysis simulations of crash tests the amount of nodes in the mast have been relatively low. This was related to the computing power available at the time which put a limitation of the size of the model. The Milliard Towers mast consisted of 2108 beam elements[1]. If we compare this to the Lattix mast[7] where the amount of elements making up the mast was around 550 000, it is easy to see how much the computational power has increased, as well as reflecting the possibilities that finite element analysis presents.

The fidelity of the mast model is increased with the amount of elements, and this should be an important consideration when modelling a mast for use in this kind of test. For different types of mast designs and material choices there are different failure modes and the model should be able to reflect the failure of the mast realistically. It’s therefore advisable to use enough elements to fully simulate detailed failure mechanisms, deformations and yielding.

Choosing a reference impactor that fulfils its role

Defining a set of rules for creating an impactor that acts as a good representation of a wing section, whether it’s a rigid impactor or a soft wing structure, will enable finite element analysis models to be consistent in predicting mast behaviour in crash scenarios for all types of masts. This is the strength of numerical analysis; the results of tests done on different types of mast will only vary because the masts are different and not because of conditional differences with the test setup. If the impactors properties are defined to a high enough level it is possible to duplicate the foundation of one test and transfer it to another.

The basis for creating impactors in finite element models in most simulations has been the recommendations for physical impactors in ICAOs design manual. The finite element modelled impactor is meant to duplicate a rigid steel semicircular tube made of steel. As the physical impactor is designed to feature as high stiffness's as possible the general strategy when creating the impactor in a finite element environment has been to model the impactor as a rigid body. This gives the impactor in essence an infinite stiffness.

Modelling the finite element impactor as a rigid body excludes problems that may arise in a transient dynamic analysis: the impactor will have no stiffness and therefore no resonating frequencies that might disturb the calculation of contact forces. As discussed with regards to the physical impactor these oscillations might affect the results. This approach will also have a resource effective impact on the simulation itself, the numerical analysis will only calculate reaction forces in the elements on the mast as these are the only ones that suffer deformations.

Modelling the impactor as a rigid body will however have an impact on the resulting contact forces from the test. As commented earlier, the conclusion of the 1998 FASG-meeting that a rigid impactor (physical) will give higher force values than a soft wing section gives the basis of the model an already conservative approach. Furthermore, modelling the impactor stiffer, and by that more conservatively, than an already conservative representation of a wing section, the resulting forces will be a lot higher than the forces a real wing would experience during impact. One could argue that using a conservative model for this sort of test will act as a safety factor against uncertainties and thereby guarantee a safe design. If however the resulting data from the test differs too much from reality, and these results create the basis for acceptance or rejection, it would be more appropriate to re-evaluate the criteria than to create inflated results.

Referring to another result from the 1998 FASG-meeting, the fact that the force and energy criteria where derived from results of tests where the impactor duplicated a wing section, means that the criteria relates to the forces experienced by an actual airplane and not a mock rigid impactor. Therefore it should not be necessary to create these inflated force values as a basis for evaluation.

Since the principal of using rigid impactors in physical crash tests is accepted by ICAO as a valid method of testing for frangibility it also validates the use of impactors in finite element analysis that inhibits the same properties as these rigid impactors. The term rigid should however not be transferred directly into the virtual environment as I've argued; providing an impactor in a finite element analysis a rigid body property moves the model further away from reality. To solve this issue the impactor could be modelled to represent a reference impactor by giving it elastic properties that are equal to those of a real reference impactor.

To duplicate a reference impactor used in physical testing requires knowledge of stiffness and mass distribution of the different parts of the reference impactor. In a general sense we can describe the impactor as consisting of the semicircular tube itself, some kind of structure that supports the tube and creates an interface for the load cells, the load cells on the interface between the backing structure and a cantilever beam, a cantilever beam and the rigid structure on the vehicle that the cantilever beam is attached to.

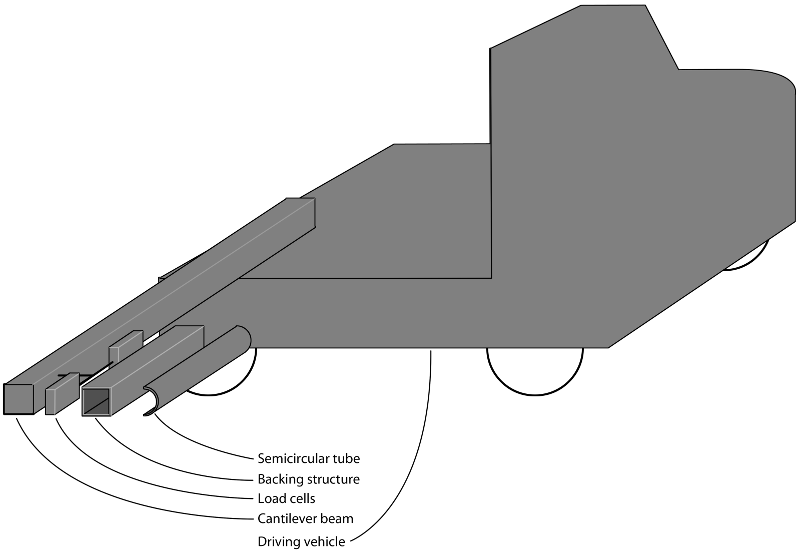

Figure 6; Overview of a general test setup

The stiffness of the semicircular tube is easily determined as the dimensions, as well as the material to this, are given by ICAOs recommendations. The structure that is backing the semicircular tube is usually a column with a square cross-section. These two elements constitute the front of the impactor, i.e. the parts between the load cells and the mast. To simplify the design it could be assumed that these parts are one part with a uniform stiffness.

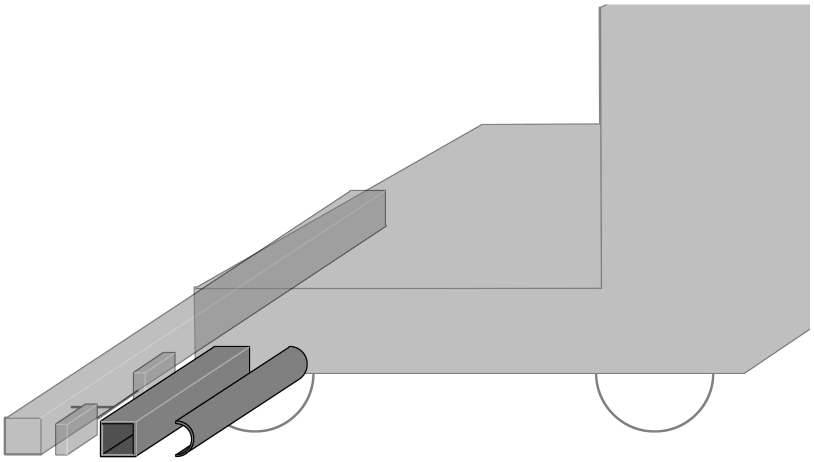

Figure 7; Showing the front part of the impactor

The rest of the impactor structure could be regarded as a beam with a given stiffness and a mass, and a point mass at the end of the beam, opposite to the impactor representing the moving vehicle. When modelling the crash test the point mass is given the initial velocity and moves along a fixed trajectory.

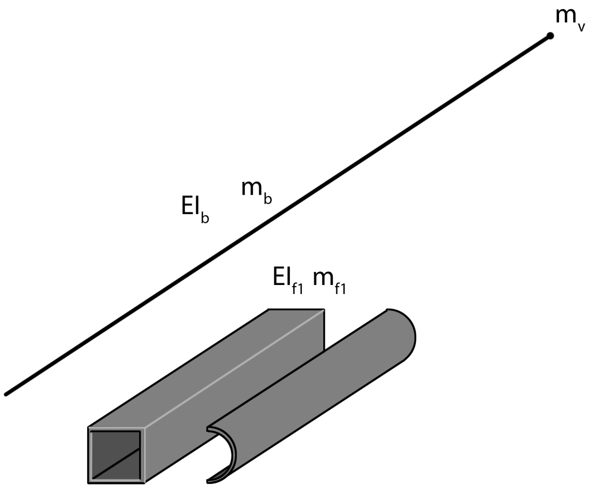

Figure 8; Showing the front part with its stiffness EI(f1) and mass m(f1), the cantilever beam with stiffness and mass and a point mass representing the vehicle

It’s also possible to move the different elements in line with each other, and simulate the stiffness of the cantilever beam as a spring element between the mass of the vehicle and the front of the impactor.

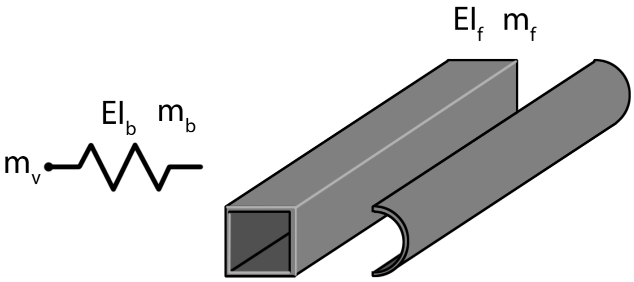

Figure 9; The cantilever beam simulated as a spring element with stiffness EI(b) and mass m(b) and the vehicular mass at the end

To achieve the same results in a finite element analysis based on a rigid impactor physical test, as those gathered in a physical test, the forces could be measured in a similar fashion. In the physical rigid impactor the load cells are mounted between the front of the impactor and the cantilever beam supporting the front. To simulate these, an amount of “boxes” equal to the amount of load cells could be modelled on the interface of the front of the impactor. These boxes should be modelled to possess the same dimensions as the load cells, and then define the nodes on the contact area between the load cells and the interface as transducer cells able to measure the contact forces. The model will then better reflect its basis, the physical impactor, with respect to how the forces are measured.

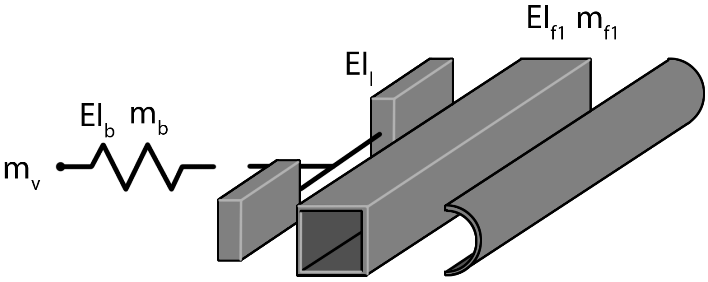

Figure 10; Showing the "boxes" representing the load cells with their stiffness

Instead of modelling boxes, which will increase complexity, the whole area of the interface between the front impactor and the cantilever beam could be defined as the contact area to be measured. This will drastically reduce complexity in the model by leaving out the stiffness of the “boxes”, as well as solving the issue of duplicating the measurement of forces from the physical impactor.

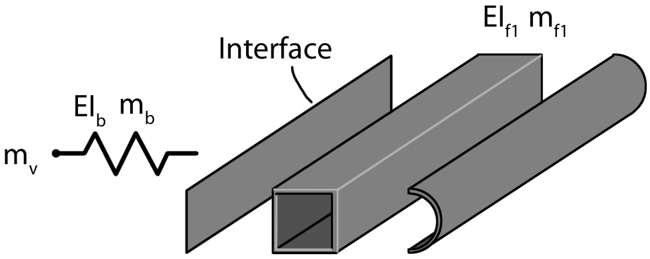

Figure 11; Showing the interface at which the contact forces can be calculated

While these strategies, if modelled correctly, may improve the accuracy of the finite element analysis, they will also increase its complexity. When simulating elastic elements crashing into each other the finite element model will conjure oscillations in the impactor that will affect the results. These oscillations can be cancelled out by introducing some sort of damping to the model. The most common form used in numerical simulations is the Rayleigh damping, a form of proportional damping that assumes that the damping matrix can be expressed as a linear combination of the mass and the stiffness matrices. The knowledge in this area is however very limited which will impede the ability to gather the required information from the physical impactor. In complex structures it will also be wrong to assume proportional damping, as this does not sufficiently reflect the actual damping in the structure.

For simple structures it's possible to measure the material constants related to resonance and damping by impulse testing. This could for example be done to the front part of the impactor.

As well as posing a complex problem with regards to defining damping ratios using proportional damping will also increase the duration of the simulation by a large degree. This will in turn increase the costs of doing the simulation.

To circumvent the complexity of finding the damping ratios of the entire structure I propose a strategy where the front of the impactor is defined as elastic while the rest of the structure is defined as a rigid body. The beam and vehicle structure is most likely stiffer and more rigid than the front of the impactor, which validates this as a realistic assumption.

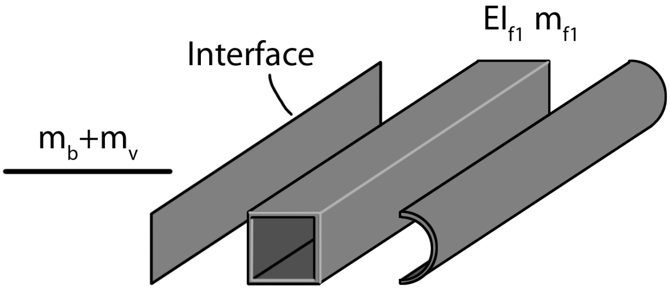

Figure 12; Showing the model where the cantilever beam is regarded as rigid

As mentioned with regards to basing the model on an airplane crashing into a mast rather than a reference impactor, it's not necessary nor practically feasible to model an entire airplane to use in the crash test. The objective of the test is to predict how an airplane will react to an impact with a certain mast, and this is today achieved by measuring the force and energy the mast impose on a wing section. The results of such a test will be able to predict rather truthfully the airplanes reactions with the exception of the exact damage it will suffer. The force a wing experience, and by extent the energy transferred, may predict in a general way how much deformation a wing will suffer, but not the exact damage.

If there is a need to realistically simulate this, the impactor, or at least its frontal part, can't be modelled as a thick semicircular steel tube. The basis of the finite element impactor can still be the same as its rigid counterpart: the mass and stiffness distribution discussed earlier should be taken into account. A proposed strategy to reach this goal is therefore to use the same mass and stiffness configuration as in *fig(x)* but use a realistically modelled wing section as the front part of the impactor.

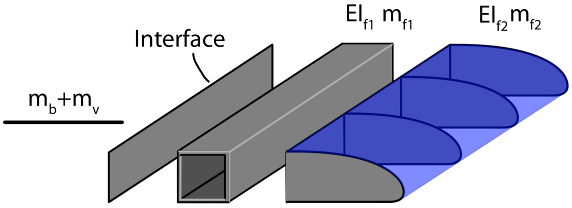

Figure 13; Showing a proposed model of a wing section impactor, the cantilever beam can either be modeled as rigid or with its stiffness in this model as well

This model approach might serve to show unique deformations related to individual types of masts, and also impact direction. It will however also in an increasingly manner, depending on how complex the structure is, exhibit the same problems that surrounds the elastically modelled rigid impactor. The damping factors for a wing section may prove even harder to discover. It should also be noted that wings used in commercial aircraft usually uses some kind of composite materials, and these more often than not have an anisotropic microstructure. This means that the modelling process will be more complex as this is hard to duplicate in a FE modelling process.

References

1. International Civil Aviation Organisation; *Aerodrome Design Manual – Part 6 – Frangibility, First Edition – 2006*
2. D. G. Zimcik; M. Nejad Ensan; and M. H. Farha (2002); *Frangibility of Airport Approach Lighting Towers*
3. M. Nejad Ensan; D. G. Zimcik; and F. B. Hsiao (2002); *Nonlienear Finite Element Analysis of Airport Approach Lighting Structures under Impact Loading*
4. D. G. Zimcik; M. Nejad Ensan; S. T. Jenq; and M. C. Chao (2004); *Finite Element Analysis Simulation of Airport Approach Lighting Towers*
5. M. Nejad Ensan; D. G. Zimcik; S. T Jenq; and F. B. Hsiao (2004); *Finite Element Impact Model of Airport Approach Lighting Towers*
6. Juhani Hanka; Markku Vahteri (1991); *Test Report Impact Test of Exel Approach Light Masts*
7. Jurek Czujko – nowatec (2008); *Juralco Aviation Masts, Juralco Aviation, Frangibility Study, NTR-2008-007*
8. J. F. M. Wiggenraad; A de Boer; and R. H. W. M. Frijns (2000); *Impact simulation of a frangible approach light structure by an aircraft wing section*
9. J. F. M. Wiggenraad; and D. G. Zimcik (2001); *Frangibility of approach lighting structures at airports*
10. A. Alipour; and F. Zareian; *Study Ralyleigh Damping in Structures; Uncertainties and Treatments*
11. Sondipon Adhikari; and A. Srikantha Phani; *Rayleigh's Classical Damping Revisited*
12. K. G. Robbersmyr; and O. K. Bakken (1997); *Impact test for Lattix Airport Approach Light Towers*