

Congruence of Life Qualification Methods and In-Service Response for Different Structural Components – Some Case Studies Encountered During the Management of the IAF Tornado Fleet

Tommaso Giacobbe

Alenia Aeronautica, Fatigue Department

[tgiacobbe@aeronautica.alenia.it](mailto:tgiacobbe@ aeronautica.alenia.it)

Arturo Minuto

Alenia Aeronautica, Fatigue Department

aminuto@aeronautica.alenia.it

GENERALS

The effectiveness of any military force depends in part on the operational readiness of the aircraft. One major item of an aircraft system affecting its operational readiness is the condition of the structure.

The structural integrity of the aircraft in service is guaranteed, generally, by a robust design of the primary structure achieved by means of detailed analysis, proper material selection and verification of the most critical areas via the execution of experimental tests for the qualification of the product.

The issues related to the reliability of structure become more important with the increase of aircraft age and much more when an extension of life against original design is required: this because fatigue on structure is a driving factor in ageing of aircraft and, moreover, corrosion phenomena may produce significant penalties both on static and fatigue strength.

Tornado programme is a typical example of these structural topics and this paper provides some arguments for a discussion about the major issues and possible solutions identified.

In order to manage the life of the aircraft fleets it is essential to know the qualification level of the structure which is related to expected usage assumed as reference during the design phase; this is the basis to be compared with the actual aircraft usage which is determined through the in service monitoring of fatigue consumption.

The structural tests are, usually, the major source of the airframe qualification, and are used to confirm or improve the results of the analytical calculations. It must be taken into account that, from structural integrity viewpoint, the most significant test is the fatigue test on the complete airframe (MAFT: Major Airframe Fatigue Test).

One of the major issues experienced is that, in order to save time and costs, during the structural test definition some compromise are set, for example, in the loading introduction and, as consequence, some items are not loaded in a representative manner. These items are tested separately with their proper loads and spectra, but often the interfaces, or the backup structure, remain uncertainly qualified.

Some inconsistencies between the expected performance in the design phase and the in service structural response is due to several causes that, during the duration (several years) of the project, contribute to modify the original design scenario. An example of this are the updating of load analysis results or the introduction of new store configurations.

Moreover the in service fatigue monitoring covers a limited number of structural “Control Points”, while the fatigue life consumption of the remaining part of the airframe is estimated by the read-across process of the “measured” data; this can cause uncertainty in the understanding of the real behaviour of the structural components as for example the movable surfaces which aren’t strongly related to the monitored locations.

Taking advantage of the experience of Tornado program this paper would be an attempt to categorize the different problems encountered in the structural management of a fleet that, after 30 years of service requires a life extension activity.

The main topics taken into account are:

- Identification of the correlation between the different qualification levels applied to different components;
- Verification of qualification status of significant structural items (SSIs) with particular attention to the interfaces between components tested in MAFT and components separately tested;
- Identification of qualification level of interfaces between systems and structure;
- Identification of recovery actions to be undertaken when qualification level is judged not adequate;
- Identification of new items requiring a dedicated monitoring because not in connection with other monitored components.

On the basis of the aforementioned issues and lesson learned during Tornado experience, a discussion is hold on the recovery actions (and possible future qualification processes) able to minimize the troubles and the penalties arising from a non homogeneous level of airframe qualification.

1.0 STRUCTURAL INTEGRITY MANAGEMENT SYSTEM

Looking to our experience (in particular on Tornado) the operational readiness of an aircraft is based on the following main features:

- A robust design
- A detailed qualification process based on the development of Structural Tests;
- A continuous monitoring of the in service fatigue consumption of the airframe;
- The embodiment of the improvements/modifications defined during the qualification phase;
- The Inspections to verify the actual status of the structure from fatigue and corrosion viewpoint.

1.1 The robust design

The robust design of the Tornado airframe is based on the accuracy of Design Criteria, Materials, Structural Configuration, Manufacturing Processes and Inspection Procedures selection .

The design criteria include the service loads history, the functional requirements, and the expected life of the structure.

Material selection is a critical element of the process. Trade-off studies, conducted between competing materials, are necessary in the selection process. Ultimate strength, yield strength, fracture toughness and stress corrosion resistance must be considered together with the expected aircraft environment.

The structural configuration development must consider the effects of design details on Fatigue control and must consider the “Structural redundancy” as an enhancement feature which maximise the structural integrity in case of load path failure.

Manufacturing processes must be selected for the critical parts such that they do not reduce the structural integrity level required by the design. Control of processes to maintain process quality is the prime consideration to meet the design goals.

Procedures for inspecting the aircraft during operational maintenance constitute the last element of the total design process.

Moreover the selection of very severe load spectra demonstrated to be the most useful choice to extend the life of the aircraft, and is probably the main topics we have to take into account in our discussions

1.2 The qualification process

The TORNADO structure is conceived under the “safe life” design criteria adopting a “scatter factor” equal to 4, having as goal a life of 4000 flight hours in 25 Years.

The fatigue qualification process has been achieved by analyses and by tests performed on the complete airframe and on components.

The Main Airframe Fatigue Test (MAFT), at the beginning planed up to 16000 T.H., has been extended up to about 21000 Test Hours.

During the MAFT development, different lives have been qualified for different components, because, in case of structural failure, some components were substituted in the Test Article.

As consequence of such events, modifications were designed and qualified, and some activities have been carried out in order to acquire a better knowledge of the fatigue “Capability” of the primary structure, and to identify maintenance actions to manage the structure when qualification level is low or uncertain

1.3 Monitoring of fatigue consumption

The monitoring is based on the recording of the main flight data (C.G. accelerations, masses, sortie code, etc.) that permit to determine, for each flight, the load time history and consequently the sequence of loading cycles; from loading cycles it is possible, by adopting opportune stress conversion functions, to determine the stress cycles history and hence the fatigue consumption.

The in service damage calculation process is compared to the design damage calculation process assuming conservatively that, at the end of fatigue test, fatigue life is zero even if no failure is occurred.

Hence the key point is the availability of correct reference spectra.

1.3.1 Reference spectra

The main source of information, for Tornado aircraft, is the Major Airframe Fatigue Test (MAFT). This test was designed to qualify the main structure of aircraft on the basis of mission profiles originally assumed.

The maximum (or minimum) loads of fatigue cycles were reproduced selecting some corner points of the manoeuvres; this selection was oriented to have representative cycles for the most important items: e.g. wing box

Moreover items that have not a primary function in the strength but are source of loads (e.g. flaps) were not installed and substituted by dummy components (Figures 1 and 2), just in order to allow a correct load introduction on the main airframe structure. This is the best compromise between the correct test article loading and the test rig simplification.

The first consequences of above mentioned compromise was that some items were not qualified on MAFT together with main structure but received qualifications on dedicated tests or via calculations only.

Another consequence was that some portion of structure, not fully represented in MAFT, were used to adjust loads introduction on main structure, and so the interface loads are not quite correct.

About the representativeness of the MAFT, it is important to note that, in particular on the wing, some components (installed as a dummy) do not contribute significantly to the wing total structural strength but, due to their dimensions and importance, could affect safety.

A significant example, as shown in Figure 3, is given by the flaps and slats that constitute about 2/3 of the total wing surface, even if the structural component constituting the main load path between wing and fuselage is the central wing box.

In order to have knowledge of the qualification of different parts of the aircraft a massive work was performed to identify how items not well represented on MAFT were qualified.

As output of this work, in general a good qualification level was found for majority of items not properly tested on MAFT, but, on the other hand uncertainties were usually found on the interfaces.

1.3.2) Service fatigue calculation

Loads cycles experienced in flight were monitored from the beginning of Tornado service activity on some “control points” that can be considered representative of the main structure (See Figure 4).

The control points can be used to estimate also the fatigue consumption of the items that, due to geometric similarity or due to the dominant load condition (for example bending moment dominated areas) may be derived directly from the monitored items. In general, in our Tornado experience, the fatigue consumption of monitored “control points” is in direct correlation with Nz variation.

For items not originally selected as control points several management philosophy, alternative to direct fatigue calculation, were applied: management by read-across with control points, managements by counts of events (e.g. undercarriage cycles, number of gun shots), routinary inspections for low risk components.

1.4 Improvements and Modifications

During the life of an aeronautical project several modification in the structural configuration may be expected.

The sources for changes may be different: improvement of production process, in service arising, qualification test results.

Light changes of the manufacturing process, for example to reduce assembly time or to reduce ecological impact, generally have not impact on the availability of the aircraft, while modification due to qualification test issues (e.g. failures) in general are embodied to enhance the fatigue life.

The Tornado experience showed that, in order to maximize the service life, it is important to determine the correct modifications point of embodiment; this means, again, that the problem to have a good evaluation of the consumed life is fundamental.

The in service findings, like wear or corrosion (and the consequent recovery actions), not directly relate to fatigue but potentially affecting structural integrity, must be accounted for when the life extension of an aircraft is required.

Anyway wear phenomena may be due to local severe load condition and consequentially may be associated to potential fatigue troubles.



1.5 Inspections

Inspections are another basis of the philosophy followed to maintain safety during a long period of service operation.

Inspection were used also to cover lack of knowledge or an insufficient available life; anyway in order to optimise their frequency it should be useful to know something about the qualification and the service spectra

2 FLEET MANAGEMENT ISSUES

From experience in the management of the fleet on the basis of elements outlined in previous paragraph, the main issues arise from the following:

- Robust design or excess in qualification
- Different qualification level for different components
- Difficulty to monitor some items
- Difficulty in monitoring coupled with uncertain qualification level.

2.1 Robust design or excess in qualification

Actually robust design is not a problem, but a “positive environment” that permits to minimise the problems concerning the life extension process of an aircraft.

The point to be discussed is if this situation can be voluntary reproduced for all aircraft

Certainly to define a design or test spectrum more severe than the expected in service gives some advantages:

- Possibility to extend the aircraft life without need of an additional qualification process.
- Easier life management for different aircraft with different severity in usage

On the other hand, we should have a more expensive test, and it is difficult to accept at the beginning of the project the necessity to schedule an excess of life qualification (both in terms of hours or in terms of severity in usage), also if this excess of life in many cases has been required.

2.2 Different qualification levels

This is probably the major issue and certainly several kinds of problems may be highlighted.

The first point is that not all the structural components are designed with the same consistency of the design database; for example the design spectra of some parts are set in different times, along the design process, with the data available at that specific time.

The second point is that some items are calculated but partially (or not properly) tested and so the reliability of the qualification activity is lower than in case of the full tested items

The third point (and in our experience the most important) is that some items (in particular interfaces) are not properly tested nor in fatigue test of major airframe nor in component tests.

This aspect may be quite common for interfaces between main structure and movable surfaces (See Figure 5)

2.3 Difficulties in monitoring

The difficulties are usually related to the load evaluation. Sometime the calculation of loads on certain items results to be unreliable and only with dedicated measurements an enhanced accuracy can be obtained.

Another significant aspect is connected with the fact that for some items no specific calculation is foreseen. This because for these items a monitoring based on read across with other structural components is judged sufficient.

A typical example of this situation were the flaps of Tornado that are a significant part of wing surface and so the loads acting on them contributes significantly to the lift not only during take-off and landing but also during manoeuvres. As consequence of this it is reasonable to read across flaps fatigue consumptions from wing box.

From service experience it was discovered that the number of take-off and landings are significantly greater than established in the original design, and will increase in case of life extension; consequentially the original ratio between manoeuvre spectrum and landing spectrum (where manoeuvres were dominants) change significantly.

This implies that a dedicated loads monitoring of the flaps, mainly during take-off and landings, become important. In fact, since the loads during take-off and landings are related to geometric position of flaps, quite different from position during manoeuvres, the fatigue consumption cannot be related to wing box consumption.

2.4 Difficulty in monitoring coupled with uncertain qualification level

This is a typical situation when we have to monitor interfaces between items of which one received test not jointly with main airframe.



In this case it may be that the interface structure, like the part of wing box where flaps or slats are attached, was not properly loaded in the main airframe test nor in the test dedicated to the involved subcomponent. So the available qualification level is only by calculation and the confirmation by test did not occur.

At the same time, for flaps and slats of Tornado, it was decided not to have a dedicated monitoring , and so this is a situation where two difficulties are summed.

Similar problem occurred also for other movable surfaces (like spoilers) but their importance is significantly lower, and so it is a minor problem.

It is interesting to note that other important components , like tailerons; also if tested separately, did not suffer the problem because it was possible to apply correct loads during the major airframe fatigue test. Looking for reasons of this difference it is important to note that the structure connecting taileron and fuselage is a “single load path” structure while the connection of flaps an slats to wing box involves many points. This indicates the difficulty to reproduce a correct load introduction with few jacks

3 RECOVERY

After the overview about the correct monitoring problems of the fleet or about lack in qualification process, it is important to discuss what improvements may be adopted both for the current programme (Tornado in this case) and for future aircraft.

The first point is the management of different qualification levels . Of course the best policy should be to have all items qualified in the same manner, but, in our experience, this was not the case of Tornado project..

To manage the actual situation the basic approach was to maintain or monitor all items against their qualification.

This was estimated possible because major items were, anyway, calculated an tested .This implies to have a life survey different for different items based on the following policy:

- A dedicated monitoring (mainly for fatigue aspects) on main control points;
- An indirect life survey, integrating the basic monitoring by read-across with the directly monitored control points, for other significant items.

This concept was applied for several years but the survey of some significant items (e.g. flaps and slats) returned different feed-backs with respect to what originally assumed, hence, it was necessary to adopt alternative policy to guarantee safety.

Different approaches may be used :

- Specific monitoring of some items for which a reliable correlation with other components is no more available
- Use of inspection to cover uncertainties
- Measurement of loads
- Extension of life by means of new test or extension of previous ones.

The first approach is theoretically the most logical but not so easy to be applied .

Generally the equations for monitoring, and in particular for loads estimation, require time and good knowledge of load models to be prepared; so if need for new equations arise after several years of service usage a long time for their production is required, also because it cannot be forgotten that the basic data for equations are quite old, difficult to be found and people originating them no longer on the project.

In our experience only some refinements of previous formulas was performed and so the main method to maintain or enhance the safety was to adopt inspections.

This approach is immediately available but may be expensive in terms of “operational readiness” but suffers of the following contradiction: for item that have a not homogeneous qualification with respect to the main structure, the most conservative assumptions must be adopted in the evaluation of inspection frequency, and where the qualification process is unsatisfactory (like in certain interfaces), again, the inspection frequency must be evaluated approximately (conservatively) because the reference data are poor.

In flight loads measurement campaign was also used in Tornado project. This policy was very important, for instance, to assess the loads on undercarriage structure that constitutes a typical example of items whose requirements are significantly changed along the design history.

For undercarriage backup structure, complementarily to the loads measurement approach, the policy of fatigue test extension was adopted; this permitted to increase the life of undercarriage backup structure, minimising the use of inspection..

An extension of fatigue test was performed also on other items, like pylons, in order to allow the carriage of stores different from those originally selected.

4 LESSONS LEARNED

Trying to summarise and categorise incongruence and troubles previously discussed and impacting on the fleet management the following list may be done:

1. Presence of not properly qualified Items
2. Items with requirements significantly changed from original assumptions
3. Items for which it is difficult to have an effective loads and stress calculation methods

The first problem is certainly the most important one because leave uncertainties that force to have precautionary (not planned and expensive) maintenance actions. The severity of this problem depends on the importance of the affected component.

In our experience, for instance, the flaps/slats interface to the wing box was a significant problem, while interfaces of minor movable surface like spoiler were a less severe problem because loads are quite small.

A remarkable case is the fitting of pylons; their qualification was affected by some approximations, but the main load were satisfactory represented. It seems to be a good compromise between test limitations (it is difficult to reproduce 3 forces and 3 moments acting on a pylon with few loading jacks) and a good qualification level associated with correct application of main loading actions.

The second problem, related to the change in the requirements, is a great trouble only when the requirement becomes more severe than the original; in the other cases the trouble is limited to a new analysis issue to demonstrate that the qualification process covered also the new requirement.

The Tornado experience is quite significant if we look to the problems of the undercarriage.

The first thing to be noted is that the undercarriage service spectrum is not influenced by the severity of the manoeuvre spectrum (i.e. the flight profile may be not severe while the landing profile is statistically severe or vice versa).

So, while for the airframe the available life can exceed 2- 3 times the qualified life (in terms of flight hours) due to the less severity of flight spectrum versus the test spectrum, the number of “available” landings remain more or less the same number of qualified landings because, on statistical basis, the severity of ground spectrum is independent from mission severity.

A direct consequence of the above is that, when the test spectrum assumed in the design phase is more severe than the service spectrum, the possibility of a life extension for the airframe is easy to be demonstrated, while for the undercarriage backup structure an extra qualification process must be done to extend the number of landings.

Moreover the Tornado experience shows that, mainly for trainer aircraft, the number of landings (touch and go) per hour is significantly greater then in the original assumptions.

The third lesson we have to take into account is related to loads estimation for service monitoring. As previously discussed it may occur that some load calculation method, oriented to fatigue monitoring, becomes necessary during the service life of aircraft.

Now it was realised that it is difficult after several years to get correct formula also because people with background knowledge useful to build necessary algorithms is no longer involved in the project. This is not a scientific issue but is anyway a fact.

An additional problem related to the fatigue loads evaluation is due to the fact that the load models, adopted in the design phase, were conceived having as goal the development of static loads (limit conditions). So also the results of flight load survey were tuned to the limits loads; this implies that some calculations are not accurate because coming from a “static load model” which is less accurate for manoeuvres typical of fatigue spectra.

5 POSSIBLE FUTURE IMPROVEMENTS

From all above considerations the first challenge consist in the optimisation of the fatigue tests rig (reduction of dummy components, optimisation of number and jack position, etc.) in order to have a good qualification of the interfaces. From our experience this aspect is very significant for interface between the main structure and movable surfaces.

The main difficulties arise from the representativeness of load introduction on the movable surfaces which, sometime, are not statically determined and hence need the use several jacks to reproduce a reasonable load distribution.

Probably it is unrealistic to think to apply correct loads on each movable surface; my personal opinion is that a good compromise could be: to select, for each family of movable surfaces, one item that can be considered “the qualification driver” to be loaded in representative manner; the other surfaces, subjected to simplified loads, should have the function of guarantee the overall test article equilibrium.

An other suggested improvement regards the availability of loads and stress calculation models. In my opinion early in the design phase it is necessary to prepare the monitoring equation for the main parts of the aircraft, also in excess to the control points we intend to monitor.

It should be useful to have a tuning or refinement of loads/stress formula not only oriented to a correct representation of limit condition but oriented to calculate the (fatigue) loads usually experienced during service missions.

The Tornado experience showed that the design spectrum in excess (as a part of robust design) is very useful to extend the aircraft life and implies a test time reduction against a test extension. Actually it is difficult to say if the approach to increase the test spectrum severity may be applied also to other aircraft programs because when the spectra are already very severe it is difficult to enhance their severity without penalties due to weight increase.



From what we discussed above it is clear that the backup structure of the undercarriage is a structure which directly influence life extension of the airframe. Furthermore a great difference in number of landings was observed between different aircraft configurations. In particular trainer aircraft cumulated a greater number of landings (touch and go) then strike aircraft.

It is too expensive to have different fatigue test, for instance one for trainer aircraft and one for squadron aircraft, to cover different requirements in landings; so in our opinion the choice to add undercarriage cycle to the major airframe fatigue test was the correct one and, probably, should be the best practice and should be the standard policy for every aircraft program.

6 STANDARDISATION

It was asked to discuss whether standardization of processes could potentially help availability of future aircraft.

Now, in my opinion the standardisation may be useful because forces the aircraft companies to think also to the long time maintainability, but actually there are many points that adverse a standardisation of issues discussed in this memory:

The first point is that any aircraft is different from others and so it is very difficult to anticipate (to standardise) what is the qualification methods or the points or parameters to be monitored in service.

The second point is that the characteristics of aircraft are negotiated with the customer and the project is not directly subjected standard airworthiness requirements

Another point, complementary to the previous one, is that the standard has the risk to produce penalties (e.g. due to increment of mass) in performances.

Anyway some improvement suggested in previous paragraph could be subject of standard not penalising performances and anyway useful to customers and industries at least as guidelines.

For instance to foresee the possibility to apply extra cycles to undercarriage backup structure may be a standard; like a standard should be the need to have on major airframe test a good representation of interface loads for major movable surfaces.

In conclusion I would suggest to move toward a “conceptual” standard that without imposing “numbers” facilitate customer and industries to think to the future management of the fleet with his differences in utilisation and different calendar lives.



Figure 1 - MAFT: dummy flaps (beams) to load fixed flap tracks



Figure 2 - MAFT: dummy slats (beams) to load wing box

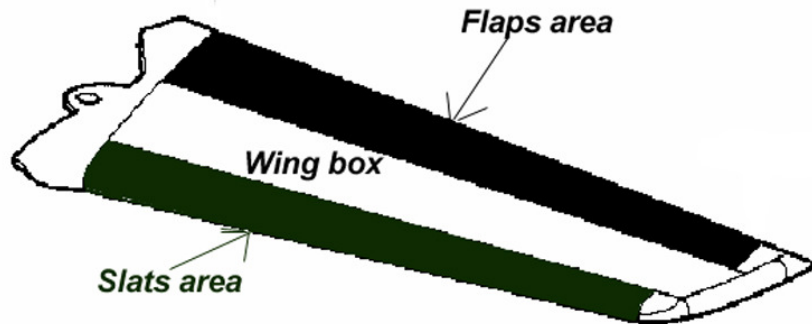


Figure 3 Wing schematic view

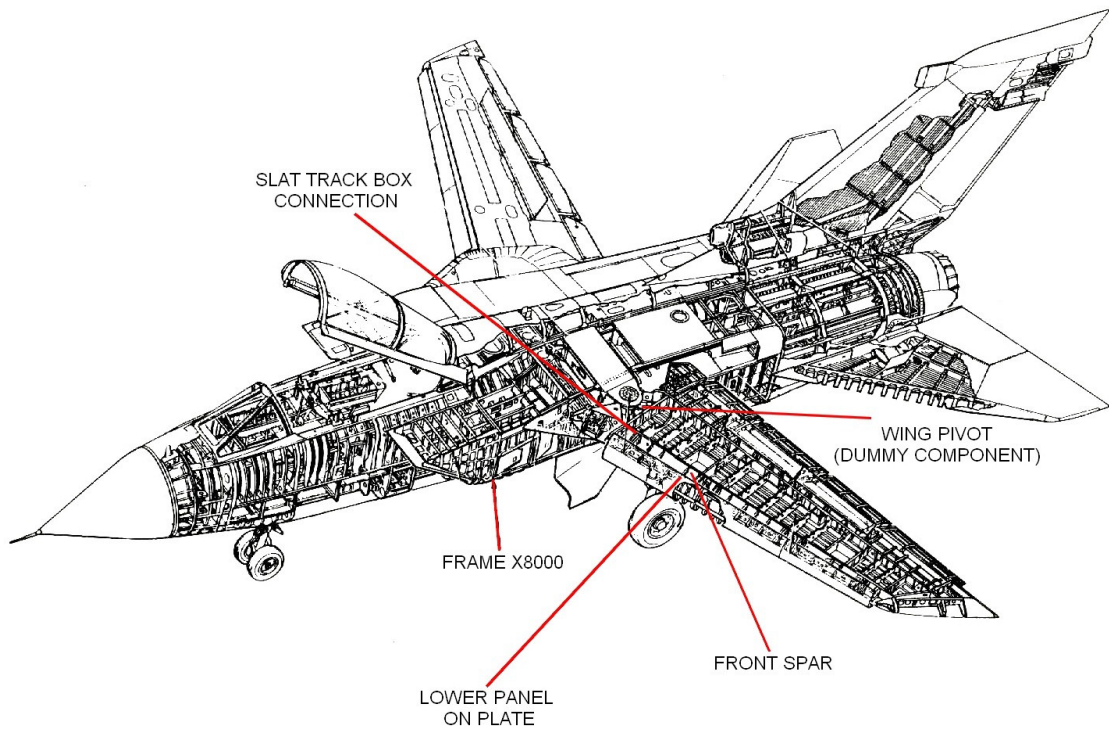


Figure 4 Monitoring control points

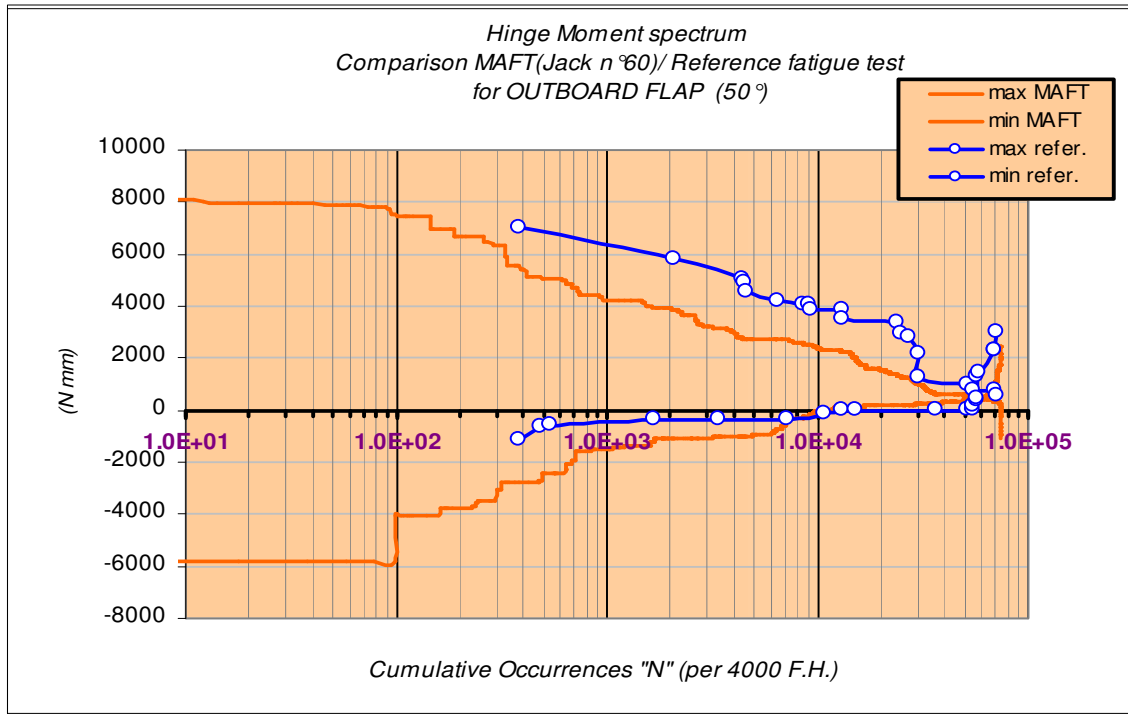


Figure 5 Example of low qualification

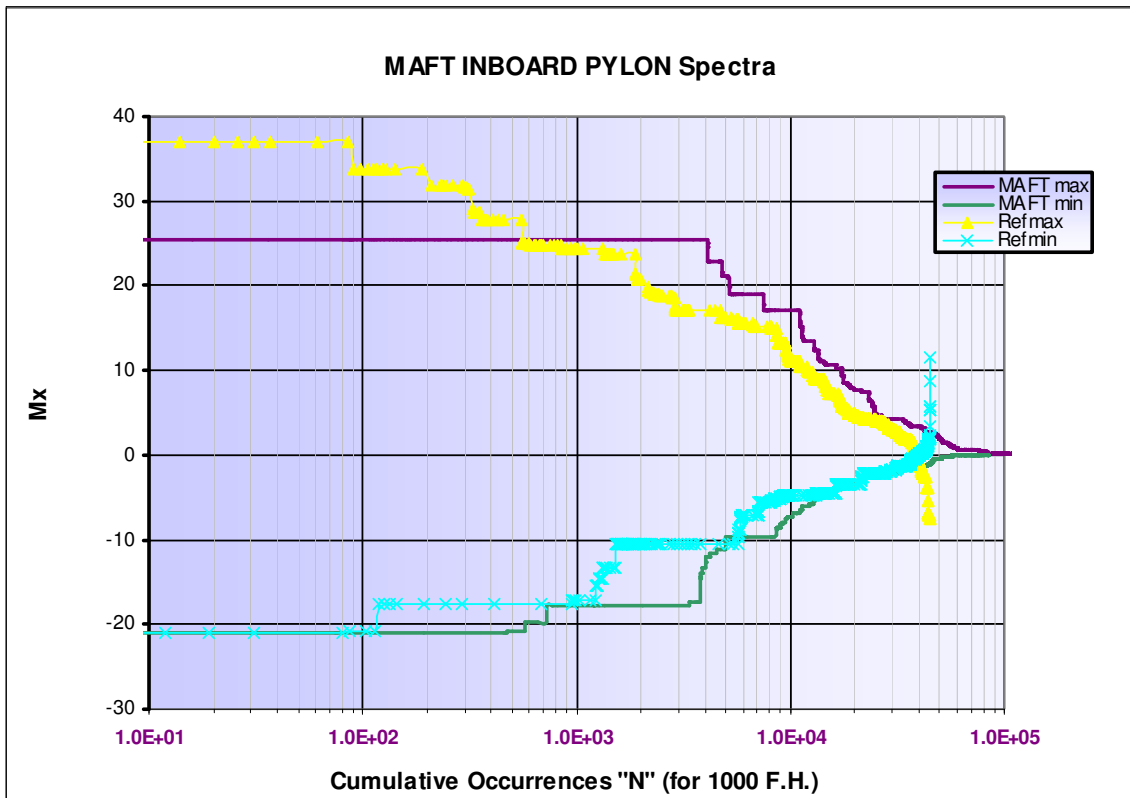


Figure 6 Example of acceptable qualification

