ENHANCING TUNNEL FAN RELIABILITY THROUGH ADVANCED FACTORY ACCEPTANCE TEST (AFAT) TO PREVENT FAILURES

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ABSTRACT

This paper introduces the concept of the Advanced Factory Acceptance Test (AFAT) and highlights its potential to mitigate tunnel fan failures.

Conventional Factory Acceptance Test (FAT) primarily focuses on basic performance criteria, such as flow, pressure, efficiency, and noise level for axial fans and thrust and noise level for jet fans. It often falls short in identifying and addressing potential issues that may lead to post-installation fan failures. AFAT takes into account additional critical factors to guarantee fan reliability and durability. These factors encompass structural integrity, material quality, vibration analysis and thermal performance.

AFAT can detect latent defects, design inconsistencies, and manufacturing deviations that often go unnoticed during a conventional FAT. Through AFAT, stakeholders in a tunnel ventilation project can reduce the risk of unexpected fan failures, enhancing operational safety and minimizing costly downtimes.

This paper proposes AFAT as a best practice to be promoted in the tunnel ventilation industry.

Keywords: tunnel ventilation, fan failures, Advanced Factory Acceptance Test.

1. INTRODUCTION

Testing is a powerful tool to assure the performance of the Tunnel Ventilation System (TVS) within designed parameters, and to prevent failures in the Tunnel Ventilation Equipment (TVE). As the tunnel ventilation is a critical system for ensuring the safety and comfort of users, a comprehensive testing approach on the ventilation equipment must be executed during the implementation of any underground infrastructure project. As extensively explained by Dr. G. Leoutsakos and others [1], the objective, through various levels of testing, is to prove and verify the quality and functionality of components, subsystems and the overall system and to transfer it into fully operational conditions. Therefore, it is needed to perform tests at different stages of the project, as follows:

1. Factory Acceptance Tests (FAT)
2. Installation Tests (IT)
3. Site Acceptance Tests or Stand Alone Test (SAT)
4. System Integration Tests (SIT)
5. System Performance Tests (SPT)
6. Trial Runs (TR)

Among all ventilation equipment, fans require special attention as they, along with the dampers, are the most critical equipment in the Tunnel Ventilation System. Fan components are subjected to quality assurance trials during manufacturing, but the first level of actual testing for the whole fan unit is the Factory Acceptance Test (FAT).

FAT is typically a contractual obligation for the fan supplier, and a significant milestone in a tunnel ventilation project. During FAT, key stakeholders, including Client, Consultant, Contractor and Supplier gather at testing facilities, usually located at manufacturer's premises or at independent laboratories, to witness a series of tests on the tunnel fans. In addition to critical commercial terms, such as partial payments or releasing bank guarantees, linked to successful FAT completion, the primary objective of FAT is to verify that fan performance and its constructive parameters comply with the project specifications.

Under the generic term of FAT are included a wide range of possible fan factory testing activities. The basic and most conventional FAT involves verifying fan performance parameters, that is flow, pressure and efficiency for the axial fans, thrust for the jet fans and noise level for both of them. However, there are projects requesting very demanding factory testing procedures, which are also referred as FAT.

This paper introduces the concept of Advanced Factory Acceptance Test (AFAT) to define a standardized and comprehensive series of tests to be conducted on the tunnel fans before delivery. AFAT includes the conventional FAT, focused in verifying performance parameters, plus additional tests, mostly oriented to guarantee the mechanical and electrical integrity of the tunnel fans.

Furthermore, this paper addresses the weakness of conventional FAT in preventing potential tunnel fans failures and explores how AFAT could lead to a more reliable and robust TVS.

2. SYSTEM AND EQUIPMENT FAILURES IN TUNNEL VENTILATION

The failures in tunnel ventilation can be classified into system failures and equipment failures, with fan failures being the primary concern. These two types of failures are closely interconnected, as system failures often lead to equipment failures, but also, equipment failures can result in system failures.

Based on fan manufacturers' records and general database of industrial equipment and components, such as the Nonelectronic Parts Reliability Data (NPRD) reports [2], the most frequent system and equipment failures in tunnel ventilation are listed in Table 1.

System failures arise from mismatches between the actual performance of the Tunnel Ventilation System and the performance needed to ensure a safe environment in the underground infrastructure. These failures have an aerodynamic root cause, either due to mistakes in the ventilation design or the inability of the selected tunnel fans to reach the specified performance parameters.

Equipment failures, primarily fan failures, are associated with electromechanical breakdowns.

While failures linked to a wrong tunnel ventilation design cannot be identified during factory testing, those related to performance, mechanical or electrical issues in the fans can be identified. Once identified, these issues must be fixed prior to equipment delivery.

On the other hand, system and equipment failures resulting from defective onsite installation and/or a lack of maintenance are not the subject of this paper, as they cannot be identified during factory testing. They shall be treated separately and prevented through rigorous verification and continuous control of these two activities.

Table 1: Failures in Tunnel Ventilation

No.	Description	Root Cause	Type
01	TVS is not able to perform to ensure a safe environment in the underground infrastructure	Wrong TVS Design	SYSTEM FAILURES
02	Axial fans do not achieve the required Flow & Pressure	Performance Issue	
03	Axial fan is in stall	Performance Issue	
04	Fan motors exceed specified power consumption values	Performance Issue	
05	Jet fans do not provide the requested nominal thrust	Performance Issue	
06	Tunnel fans do not reach specified acoustic levels	Performance Issue	
07	Tunnel fans under high vibration levels	Mechanical Issue	EQUIPMENT (FAN) FAILURES
08	Tunnel fans under vibration resonance due to natural frequencies	Mechanical Issue	
09	Reversible tunnel fans do not withstand dynamic forces due to consecutive cycles of reversal operation	Mechanical Issue	
10	Impeller’s damages under peak operation stress	Mechanical Issue	
11	Impeller comes into contact with the fan casing	Mechanical Issue	
12	Blade design or material does not withstand mechanical stresses while full speed operation at high temperature	Mechanical Issue	
13	Motor overheating during fan continuous operation	Electrical Issue	
14	Fan electro-mechanical integrity or performance fails while full speed operation at high temperature	Mech & Elect Issue	

3. CONVENTIONAL FAT TO IDENTIFY FAN PERFORMANCE ISSUES

3.1. First Article Inspection (FAI)

Before to proceed with any kind of factory acceptance testing procedure a First Article Inspection (FAI) shall be conducted. FAI consists in a visual and dimensional verification along with a materials certifications review of a fan sample selected by the customer among a quantity of units manufactured as per project’s requirement.

3.2. Aerodynamic performance test for tunnel axial fans

This test is conducted to verify the duty point (Flow & Pressure) and efficiency of axial fans. It is usually performed according to standards ANSI/AMCA 210-16 [3] or ISO 5801:2017 [4]. Through the test, ambient temperature, fan speed and pressure values must be recorded, at a minimum of 10 operating points. Adjustments to the auxiliary fan at the test bench, the Variable Speed Drive (VSD) and/or auxiliary damper are made accordingly.

The test shall cover the full operational speed of the fan, from maximum flow to zero flow. This is essential for verifying the stability of fan operation along the entire characteristic curve and identifying how external factors, such the piston effect, could potentially shift the fan operation into stall. Tunnel fans with stall-free characteristics curves ensure safe operation under all conditions.

Passing criteria (as per point 10.1.2.1 of AMCA 211-23 [5]):

- ✓ Airflow tolerance ± 5 % of specified values
- ✓ Pressure tolerance $(1\text{-}0.05)^2 \leq P \leq (1+0.05)^2$
- ✓ Power tolerance ± 7.5 % of specified values
  NOTE: Tolerance applies along the whole fan curve

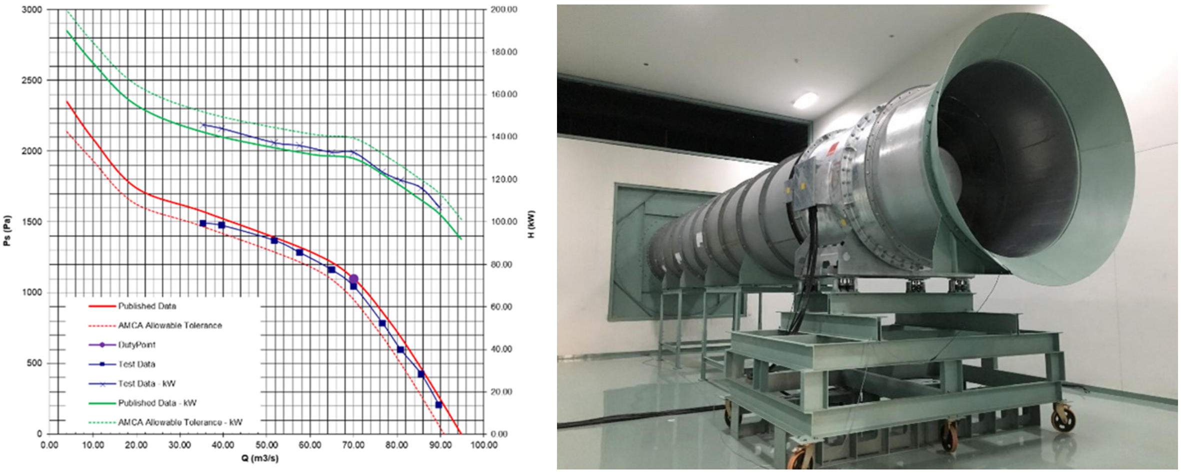

Figure 1: Stall-free characteristic curve and photo of tunnel axial fan under aerodynamic performance test

By conducting this test, the following failures (as numbered in Table 1) are prevented:

- Failure No. 2: In case the axial fan is not able to reach the specified flow and pressure values, the TVS will not perform as designed, compromising the tunnel safety.
- Failure No. 3: When the axial fan is in operation during certain time beyond its stall limit, a catastrophic impeller breakage may happen.
- Failure No. 4: The fan motors exceeding the specified power consumption values could lead to frequent tripping out on the electrical installation. Additionally, the operational cost related to higher power consumption will be increased.

3.3. Thrust force test for tunnel jet fans

This test verifies the nominal thrust of jet fans. It is typically conducted in accordance with standards ANSI/AMCA 250-22 [6] or ISO 13350:2015 [7]. The jet fan shall run for10 minutes for stable readings of thrust force, temperature and speed.

Passing criteria (as per point 10.3.2.1 of AMCA 211-23 [5]):

- ✓ Thrust force tolerance - 6 % of specified values.
- ✓ Input power tolerance + 5 % of specified values.

By conducting this test, the following failures (as numbered in Table 1) are prevented:

- Failure No. 5: Verifying the specified nominal thrust during testing ensures that, once installed in the tunnel, the jet fans will generate the critical velocity to prevent smoke backlayering in case of fire. A failure on this point will compromise the performance of the longitudinal ventilation system, leading to an unacceptable level of risk in the tunnel.
- Failure No. 4: Similar consequences to those explained in section 3.2 regarding this failure.

3.4. Sound test for tunnel fans

This test verifies the sound power level of tunnel fans. It is typically conducted according to standards ANSI/AMCA 300-14 [8] or ISO 13347-2:2004 [9]. The sound test is performed after the fan's aerodynamic performance test has established the exact duty point and operating speed.

Sound Power Level (SWL) must be measured for each of the 8 octave band frequencies. The fan's overall SWL is not representative of its actual acoustic characteristic and does not provide sufficient data on sound attenuators' outcomes.

Passing criteria (as per AMCA 311-16 [10]): Measured SWL values of the tested fan shall not exceed the published SWL values by more than 6dB in the first octave band of frequency and 3dB in any other octave band.

By conducting this test, the following failure (as numbered in Table 1) is prevented:

- Failure No. 6: Excessive noise level from tunnel fans can impact the health and well-being of residents near the tunnel portals or the ventilation shafts of the underground infrastructure. Furthermore, in emergency conditions, when the fans are operating at full speed, the noise should not exceed specified values to prevent voice messages or other acoustic signals from being heard by users of the underground infrastructure during evacuation.

4. AFAT TO IDENTIFY FAN MECHANICAL AND ELECTRICAL ISSUES

4.1. Vibration test

The purpose of the vibration test is to assess and verify that the fan operates within acceptable vibration levels, ensuring structural integrity, minimizing potential damage, and guaranteeing reliable long-term performance. This test is typically conducted according to standards ANSI/AMCA 204-20 [11] or ISO 14695:2003 [12].

Passing criteria (as per tables "6.1- Fan application Categories for Balance and Vibration" and table "8.2 – Vibration Limits on Factory Test" of ANSI/AMCA 204-20 [11]):

- ✓ For tunnel Axial fans $\leq$ 75 kW is requested category BV-3
- ✓ For tunnel Axial fans $\geq$ 75 kW is requested category BV-4
- ✓ For tunnel Jet fans is requested category BV-4
  NOTE: An upgrade into category BV-5 will improve fan's longevity.

By conducting this test, the following failure (as numbered in Table 1) is prevented:

- Failure No. 7: As extensively reported in many technical documents, excessive vibration levels in tunnel fans can lead to major failures in short or medium terms. Additionally, high vibrations reduce the operational life of the fan in the long term.

4.2. Natural frequency test

Natural frequency is an object's innate vibration rate when excited. Applying a force at this frequency creates a resonance effect, potentially leading to structural failure due to escalating oscillations.

The natural frequency test verifies that the fan blade's natural frequencies are outside of the fan's operational range. The impact test is one of the most commonly used methods to identify natural frequencies. It is carried out with an impact hammer applying a minor force in the fan blade to identify frequencies where oscillations are amplified.

Passing criteria: No natural frequency shall occur from 0 to 300 % of the fan operating speed. For example, in a fan with an operating speed of 1,500 rpm (25 Hz) there should not be any natural frequency between 0 and 75 Hz.

By conducting this test, the following failure (as numbered in Table 1) is prevented:

- Failure No. 8: In the event of vibration resonance generated by natural frequencies, there is a serious risk of catastrophic impeller disintegration.

4.3. Reversal test

This is an operational test to be conducted on reversible fans. The procedure involves running the fans at full speed during 7 consecutive periods of 30 minutes, alternatively in forward and reverse, to complete a total operation time of 3 hours and 30 minutes. The insulation resistance of the motor winding is measured before and after the test to verify that there is not any drop or change due to the heat generated during reversal operations.

Passing criteria: The fan must run smoothly for every operational cycle, remaining securely intact and maintaining mechanical integrity on all its parts throughout the test.

By conducting this test, the following failure (as numbered in Table 1) is prevented:

- Failure No. 9: The mechanical integrity of the fan could be compromised if it has not been designed with sufficient mechanical robustness to withstand the demanding dynamic forces created during reversal maneuvers. Special attention is required in cases where the fans are operated with direct starting or autotransformer, as a pick of up to 7 times the rated current is supplied to motor over 15-30 seconds and the heat generated in short period could have a negative impact in winding insulation. Alternatively, soft-starter or inverter provide a soft motor starting and reversibility.

4.4. Overspeed test

The overspeed test is conducted to verify that the impeller can withstand centrifugal forces and stresses beyond its full operational speed with a sufficient safety margin. Typically, the overspeed test is performed at 125 % of the normal operating speed.

Passing criteria: Blade measurements are compared before and after the test. Tip clearance and blade angle must remain unchanged, with an allowable measurement tolerance of ± 1 mm for tip clearance and ± 1 degree for blade angle.

By conducting this test, the following failures (as numbered in Table 1) are prevented:

- Failure No. 10: The impeller may experience peak mechanical stresses beyond its nominal speed, particularly in situations like the piston effect in the tunnel. This can result in serious damages, including catastrophic disintegration.
- Failure No. 11: Peak mechanical stresses on the impeller can lead to elongation or deformation on the fan blades, reducing the tip clearance between the impeller and the fan casing. In the event that the impeller, rotating at its maximum speed, comes into contact with the fan casing, it will break.

4.5. Tri-Axial strain gauge test

The Tri-Axial strain gauge test for an impeller involves measuring strains under operating conditions by attaching sensors at tip and middle position of the blade, and at the hub. The strains are measured while the impeller is running for five to ten minutes and using formulas and standards to calculate the stress experienced by the blade.

Passing criteria: The stress found on the blades and impeller hub shall not exceed 60% of the material yield strength at specified operational high temperature (i.e. 250ºC, 300 ºC, 400 ºC).

By conducting this test, the following failure (as numbered in Table 1) is prevented:

- Failure No. 12: During fan operation at emergency mode, the high temperatures reduce the mechanical strength of the blade material, typically aluminum alloy. If the actual operational stresses exceed the blade's mechanical resistance at high temperature, it leads to impeller breakage and subsequently to a major failure on the TVS during the most critical emergency situation.

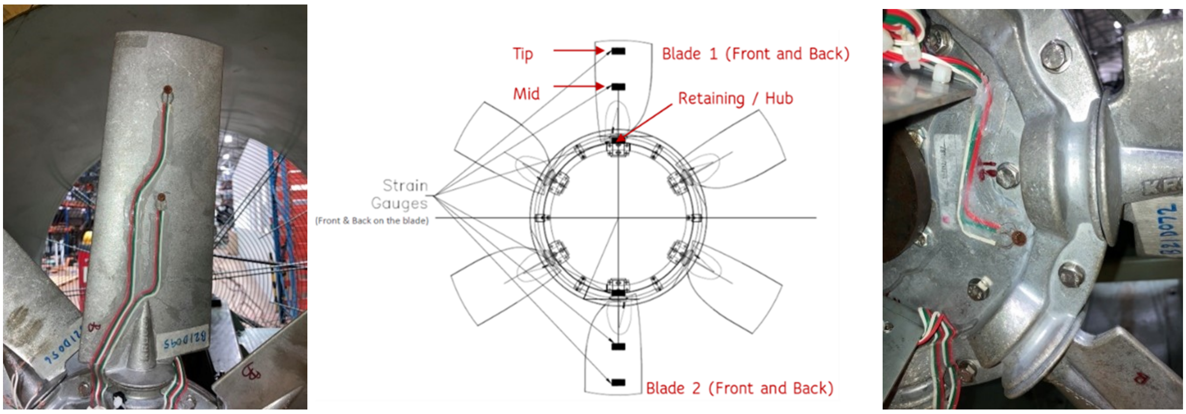

Figure 2: Tri-axial strain gauge test. Photos and impeller layout with sensors location

4.6. Run-in 24 hours test

Similarly to the reversal test, the run-in 24 test is an endurance operational test consisting of running the fan continuously at ambient temperature for 24 hours. Reversible fans shall operate 12 hours in forward and 12 hours in reverse.

Passing criteria: Motor fan shall not overheat. The motor temperature shall rise within the allowable limit as per its insulation class. Additionally, the fan shall remain securely intact.

By conducting this test, the following failure (as numbered in Table 1) is prevented:

- Failure No. 13: In case of motor overheating during continuous fan operation, the lifetime of the motor will be reduced. Additionally, it could lead to the motor burn out.

4.7. High temperature test

Besides of high temperature certificates to be provided for tunnel fans, it is recommended, especially in major projects, to perform high temperature tests on the actual fans intended for installation. These "ad hoc" tests ensure the fan's resistance and performance in case of a fire. Tests shall be conducted as per Annex C4 of the standard EN 12101-3:2015 [13] where a dual-purpose fan shall go through warm up, heat up and high temperature test phases.

Passing criteria: Testing temperature shall be maintained within 0 and +25 ºC. Static pressure difference (corrected according to air density) shall remain within -20 % +50 % of the measurement taken at the end of warm-up cycle. Additionally, fans must be inspected after the test and all parts must remain physically intact.

By conducting this test, the following failure (as numbered in Table 1) is prevented:

- Failure No. 14: A fan failure under emergency operation at high temperature, is the worst possible event for the safety of any underground infrastructure, as the evacuation of users and the intervention of fire brigades and emergency services will be compromised. Hence, all possible measures must be taken to prevent this scenario.

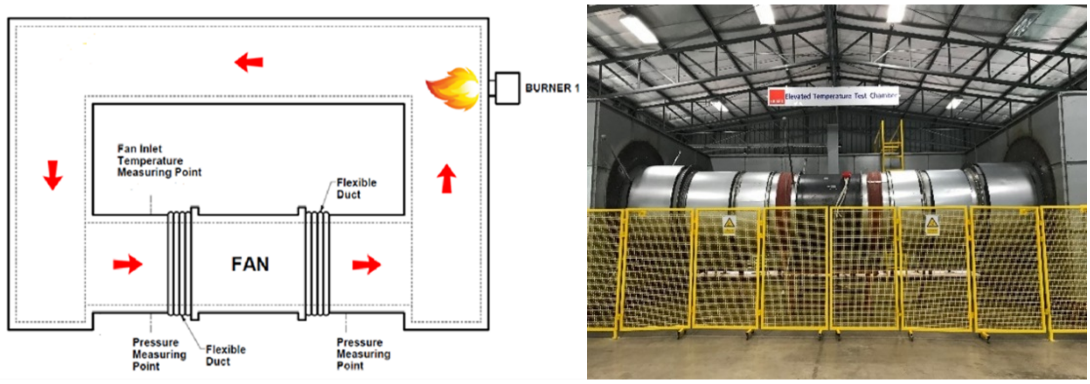

Figure 3: High temperature test for tunnel axial fans. Test bench layout and actual photo

5. SUMMARY AND CONCLUSION

FAT is defined on project basis and its level of testing varies for each project. However, conventional FAT is not enough to guarantee fan quality and reliability. AFAT (Advanced Factory Acceptance Tests) is a standardised factory testing procedure comprising 10 tests. AFAT not only verifies fan performance parameters as in conventional FAT, but also conducts additional tests to secure the mechanical and electrical integrity of fans.

6. REFERENCES

[1] Leoutsakos G., Kouropalatis A., Filis P. "Testing and Commissioning of Metro Tunnel Ventilation Systems". 19th International Symposium on Aerodynamics, Ventilation and Fire in Tunnels. Brighton (UK) 28th-30th September 2022.

[2] "NPRD-2023. Nonelectronic Parts Reliability Data". Quanterion Solutions Incorporated. 2023.

[3] ANSI/AMCA 210-16 /ASHRAE 51-16 "Laboratory Methods of Testing Fans for Certified Aerodynamic Performance Rating".

[4] ISO 5801:2017 "Fans – Performance testing using standardized airways".

[5] AMCA 211-23 "Certified Ratings Program – Product Rating Manual for Fan Air Performance".

[6] ANSI/AMCA 250-22 "Laboratory Methods of Testing Jet Fans for Performance".

[7] ISO 13350:2015 "Fans – Performance testing of jet fans".

[8] ANSI/AMCA 300-14 "Reverberant Room Method for Sound Testing of Fans".

[9] ISO 13347-2:2004 "Industrial fans – Determination of fan sound power levels under standardized laboratory conditions. Part 2: Reverberant room method".

[10] AMCA 311-16 "Certified Ratings Program – Product Rating Manual for Fan Sound Performance".

[11] ANSI/AMCA 204-20 "Balance Quality and Vibration Levels for Fans".

[12] ISO 14695:2003 "Industrial fans – Method of measurement of fan vibration".

[13] EN 12101-3:2015 "Smoke and heat control systems – Part 3: Specification for powered smoke and heat control ventilators (Fans)".