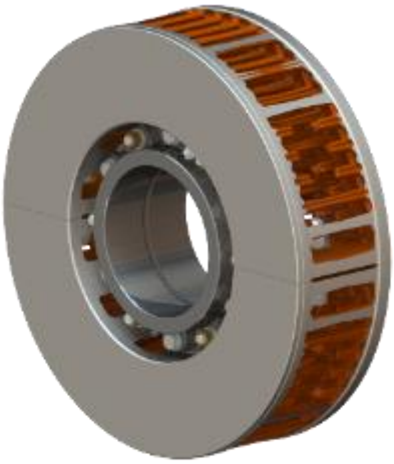
WORK PACKAGE 3 (WP3)

Laboratory testing and UIC standard compliance

PROJECT DELIVERABLE 3.1

REPORT ON LABORATORY TESTING



FUTUre RAil freight transport: cost-effective, safe, quiet and green! – FUTURA

The FUTURA project has received funding from the European Union`s Horizon 2020 research and innovation programme under grant agreement No.700985

January 2018

TABLE OF CONTENTS

DOCUMENT AUTHORS AND REVIEWERS

Lead Authors

Name	Organization
Juraj Sloboda	VÚD
Michal Kais	VÚD
Michal Vršanský	VÚD

Reviewers

Name	Organization
Ivan Smolej	KOVIS d.o.o
Alen Šinko	KOVIS d.o.o
Mitja Črpič	KOVIS d.o.o
David Deržič	KOVIS d.o.o

LIST OF FIGURES

LIST OF TABLES

INDEX OF ABBREVIATIONS

DRFB	Divided rail freight brake
UIC	International Union of Railways
TSI	Technical Specification for Interoperability
EN	European Norm
ISO	International Organization for Standardization
DB	Deutsche Bahn
VT	Visual Testing
MT	Magnetic particle Testing
UT	Ultrasonic testing
RT	Radiographic examination
CFD	Computational fluid dynamics
FEM	Finite Element Method
CAD	Computer Aided Design
HTC	Heat transfer coefficient
MS	Material Specification

1 INTRODUCTION

The scope of the document is to present the laboratory testing of DRFB disc prototypes, and compare their compliance against requirements defined in report D1.1.

The purpose of laboratory tests was to check frictional, thermal and another mechanical characteristic of DRFB disc. The scope of tests were carefully chosen by VUD, as an expert in laboratory testing, and Kovis, as an expert in the field of designing brake discs. These tests were absolutely needed to confirm computer numerical calculations, and to compare the results to requirements.

Within this work package, the following mechanical and dynamical tests were conducted in the laboratory:

- Tensile tests (sigma-epsylon diagrams),
- Hardness tests (Vickers),
- Fatigue material tests (S-N curves),
- Charpy tests (ISO-V notch),
- Fracture toughness
- Local noise measurements during braking
- Local noise measurements (while rotating the DRFB disc at certain speeds)
- Temperature measurements by PT100 and PT1000 thermocouples at different positions on DRFB disc crown and hub during single and multiple braking
- Vibrations measurements (Imbalance measurements)
- Coefficient of friction measurements between the DRFB disc and braking pads at different velocities
- Coefficient of friction measurements between the DRFB disc and braking pads at material degradation (corrosion, dust, humidity, wet conditions)
- Ventilation tests (power losses)
- Measuring the wear and volume of material at single and multiple braking, determining the mass (grams) and the volume of used material (cm3/MJ)

Reference standards:

Table 1: Reference standards

Document Nr.	Revision	Title
ISO 6892-1	2016-07	Metallic materials -- Tensile testing -- Part 1: Method of test at room temperature
ISO 148-1	2016-10	Metallic materials -- Charpy pendulum impact test -- Part 1: Test method
ISO 6507-1	2005-12	Metallic materials -- Vickers hardness test -- Part 1: Test method
ISO 15653	2010-04	Metallic materials -- Method of test for the determination of quasistatic fracture toughness
UIC 541-3	2010-07	Brakes – Disc brakes and their application – General conditions for the approval of brake pads
STN 42 0363	1986-10	Metal testing. Fatigue testing of metals. Methodology of testing
ISO 12107	2012-08	Metallic materials -- Fatigue testing -- Statistical planning and analysis of data
TSI 2008/861/EC	2013-03	Technical specification for interoperability relating to the subsystem ‘rolling stock freight wagons’ of the rail system in the European Union
TSI 2011/291/EU	2011-04	Technical specification for interoperability relating to the ‘Rolling stock’ subsystem for conventional rail ‘Locomotives and passenger rolling stock’
EN 14535-1	2005-12	Railway applications – Brake discs for railway rolling stock– Part 1
EN 14535-3	2012-07	Railway applications – Brake discs for railway rolling stock– Part 3
EN ISO 17025	2005-05	General requirements for the competence of testing and calibration laboratories
EN 1561	2011-12	Founding – Grey cast irons
UIC 813	2003-12	Technical specification for the supply of wheelsets for tractive and trailing stock - Tolerances and assembly
EN 1370	2012-02	Founding – Examination of surface conditions
ISO 2768-1	1999-03	General tolerances – Part 1: Tolerances for linear and angular dimensions without individual tolerance indications
DIN 27205-2	2008-12	State of railway vehicles – brake – Part 2: Disc brake, mechanical part
DIN 27205-3	2010-11	State of railway vehicles – brake – Part 3: Ventilated axle mounted brake discs

2 TECHNICAL REQUIREMENTS

2.1 Environmental requirement

The DRFB disc will be used for freight wagon bogies during normal European weather conditions.

The following conditions broadly apply:

- Ambient temperature: -25ºC to 70ºC.
- Occurring operation temperature corresponding to heat calculations brake disc.
- Relative humidity: 30 to 100%.
- Rain, snow, ice, ozone, smog, direct sunlight.
- Sand, braking and iron oxide dust (abrasion wheel / rail) and sandstorms.
- High water up to 50mm upper side track.
- Snow up to 150mm upper side track.
- Precipitation: hail, sleet, snow also frost and thaw alternating.
- Fog.
- Pollution by:
    - Grease and oily substances.
    - Toilet waste.
    - Brake dust.
    - Cleaners, detergents, etc.

2.2 Operational requirements

The brake disc shall be suitable to operate under following condition:

Table 2: Operational condition

	Unit	Value	Remark
Maximum velocity	km/h	120 (optional 160)	
Wheel diameter new/worn	mm	920/840	
Maximum axle load	T	22.5 (25 optional)	
Annual kilometers	km per year	50000	
Life time	km	1600000	

2.3 Characteristics of DRFB disc

The geometry and measurements must apply to EN 14535-1.

Table 3: Characteristics of DRFB disc

Item	Details/Description	Remarks
Outer diameter	590mm (610 optional)	See EN 14535-1
Inner diameter	320mm	See EN 14535-1
Connection crown/hub	bolted	
Connection hub/axle	Shrunken/Pressed	
Braking radius	230/233	UIC 541-3
Material	Cast iron	
Imbalance value	max 16gm	Marked on the outer surface of the discs
Minimum wear	7mm	Limit indication shall be presented on outer diameter of the disc

2.4 Brake pads

Table 4: Characteristics of DRFB disc pads

Item	Details/Description	Remarks
Pad thickness	24 or 35	UIC 541-3
Pad braking surface	350 mm^2	UIC 541-3
Pad material	organic/sintered	
Interface	Standard interface	UIC 541-3

2.5 Wear limit

The disc must ensure the performance without any limitation at least to the wear of 14 mm (7 mm per side) of the friction surface of the crowns: this limit must be visible along the outer cylindrical surface, from both sides according EN 14535-1.

Minimum thickness of the friction ring (per side) should be 14mm.

2.6 Unbalance

The level of static or dynamic unbalance shall comply with EN 14535-1, part 5.3.7: unbalance class 2 (< 16 gm).

2.7 Oscillation (runout)

Every complete brake disc, and disc itself, shall be checked for oscillation (squareness, runout) and must comply with the drawing indicated values.

2.8 Marking

2.8.1 DRFB disc Crown

The marking of the DRFB disc crown must be compliant with the reference drawings. Every DRFB disc crown has a unique serial number. With this serial number, it must be possible to track the brake disc from cast process until final product. The serial number must be printed on the test reports.

The location of the unbalance, the value of the unbalance must be marked on the brake disc in gm.

On one of the rough surfaces of the braking of the crown or in the field, immediately after the pouring, there must be following markings:

- Batch number.
- Coding of the supplier.
- Month and year of manufacture.

2.8.2 DRFB disc Hub

The marking of the DRFB disc hub must be compliant with the reference drawings. Every DRFB disc hub has a unique serial number. It must be possible with this serial number to track the brake disc hub from forging process until final product. The serial number must be printed on the test reports.

The location must be marked on the brake disc hub.

On one of the overhead surfaces of the braking of the disc hub, immediately after the forging – during trimming process, there must be following markings:

- Type of disc hub.
- Coding of the supplier.
- Number of drawing.
- Month and year of manufacture.
- Batch code.

2.8.3 DRFB disc

On the finished brake disc there must be following marking:

- Brake disc dimension.
- Brake disc serial number.
- Month of production.
- Year of production.
- Quality control stamp.

2.9 Surface roughness

The surface roughness should be such that unacceptable stress during assembly is prevented.

The surface roughness for the wear surface and hub is:

- Friction wear surface: $Rz \leq 3{,}2$.
- Hub hole: $Ra <= 1{,}6$.

2.10 Mounting

A complete brake disc (disc + hub) will be mounted by press force or by shrunk method. The mounting process shall be executed according to the proper manual (information how to mount the brake disc correctly (pressure, press liquid) and which tools should be used for mounting and demounting).

2.11 Requirements concerning the materials of DRFB disc crown

The material for DRFB disc crown construction shall have chemical composition and mechanical properties that fall within the tolerance provided for the design. The used materials may be:

- Gray (lamellar) cast iron.
- Ductile cast iron.

2.12 Requirements concerning the materials of DRFB disc hub

The material for DRFB disc hub construction shall have chemical composition and mechanical properties that fall within the tolerance provided for the design. The used materials may be:

- Steel for quenching and tempering.(for example, according standards EN 10083-2, EN10083-3 or EN 10293)

2.13 Complete disc

The tests and examinations to which the complete disks are to be submitted are as follows:

- Visual and dimensional inspection.
- Balancing test.
- Runout test.

2.13.1 Visual and dimensional inspection

It aims to verify the completeness and correctness of the assembly and of all the constituent parts of the disc according to the related drawings.

2.13.2 Balancing test

The balancing of the entire disc may be done either with static or dynamic balancing machines that the sensitivity of the apparatus is such as to allow the transaction to be completed with the required accuracy. After locating the diametrical plane on which it manifests the imbalance of the disc, we will proceed with the operation of balancing. For it must be observed the following:

- The imbalance in excess of the allowable limit must be eliminated only by removal of metal from cold areas provided for in the design and preferably on the outer cylindrical surface of the crowns or cooling fins.

A complete disc will be considered balanced when the residual unbalance will be contained below the values predicted by the design of the disc itself.

In any case, the residual unbalance of the disc brake shall not exceed that provided for Class 2 in section 5.3.7 of EN 14535-1.

The rest imbalance of the disc must be clearly marked on the place of highest imbalance value.

2.13.3 Runout test

The maximum runout of the braking surfaces of the crown must be verified by mounting the disc on a cylindrical pin with a pressure sufficient to avoid any mutual sliding and resting, in correspondence to the two flow rates of the pin, on two supports such as to allow complete rotation of the disc in a perfectly vertical plane.

The detected value must not exceed the limit imposed by the design of the disc.

2.14 Preservation

The surfaces, which are to be protected, are indicated on the reference drawing.

Unless otherwise agreed the protection is:

- DRFB disc crown – outside: ANTICORIT DFW 330 IP.
- Hub – outside: ANTICORIT DFW 330 IP.

3 MECHANICAL TESTS OF PROTOTYPES

From each prototype of DRFB disc and hub, samples of basic raw material were taken for different mechanical tests. Followed by this, samples were machined according to the test standard, for which they were used. Samples were prepared for following tests:

- Tensile tests (sigma-epsilon diagrams),
- Hardness tests (Vickers),
- Fatigue material tests (S-N curves),
- Charpy tests (ISO-V notch),
- Fracture toughness

4 PREPARATION OF SAMPLES

At first, samples of different prototypes of DRB disc and hub were delivered to the laboratory. Followed by this, samples were marked and sent for mechanical machining, where they were machined on the final shape, suitable for mechanical testing.

Figure 1: Samples of DRFB disc and hub

From raw material, samples were taken for material tests. Samples were taken from discs and hubs in such way that all the critical places of the finished products were covered.

For this reason, the samples were deployed throughout the whole discs and hubs, both in vertical and horizontal planes (see figures 2-3). Additionally, there were multiple samples taken from the same locations, the number of which was given by space options.

It was from 3 to 15 samples from one location. The samples were then machined according to the requirements of the relevant standards. For each prototype, samples were taken from the same sides.

Figure 2: Cut samples of DRFB disc hub

Figure 3: Cut samples of DRFB disc crown

4.1 Tensile test samples

Samples were machined in accordance with standard EN ISO 6892-1 “Metallic materials — Tensile testing - Part 1: Method of test at room temperature”, article 6.

Preferred test pieces have a direct relationship between the original gauge length, Lo, and the original cross-sectional area, So, expressed by the equation Lo = k √So , where k is a coefficient of proportionality, and are called proportional test pieces. The internationally adopted value for k is 5,65. The original gauge length shall be not less than 15 mm. When the cross-sectional area of the test piece is too small for this requirement to be met with, k = 5,65, a higher value (preferably 11,3) or a non-proportional test piece may be used.

Machined test pieces shall incorporate a transition radius between the gripped ends and the parallel length if these have different dimensions. The gripped ends may be of any shape to suit the grips of the testing machine. The axis of the test piece shall coincide with the axis of application of the force. The parallel length, Lc, or, in the case where the test piece has no transition radii, the free length between the grips, shall always be greater than the original gauge length, Lo.

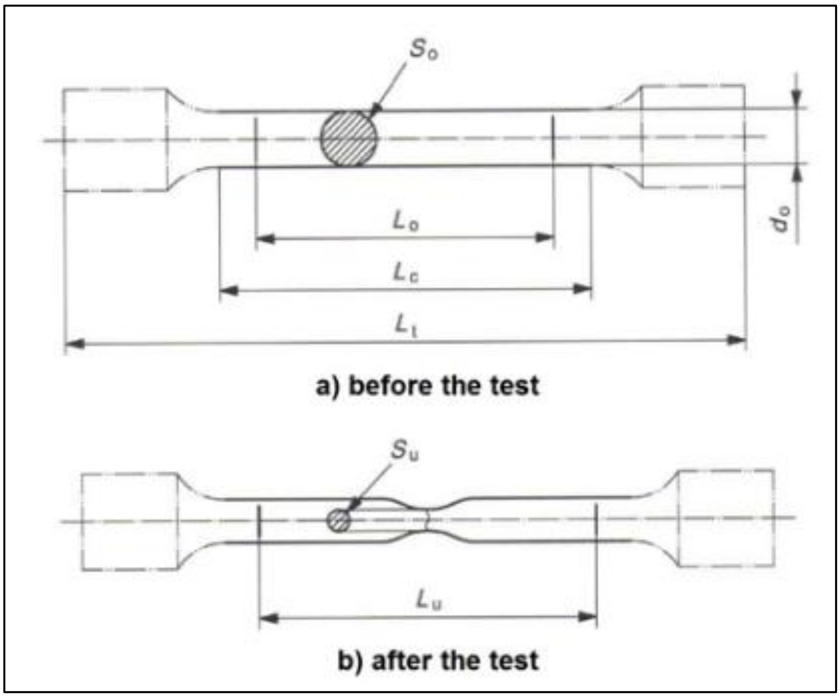


Figure 4: Shape and dimensions of tensile test samples

- S_o - original cross-sectional area of the parallel length
- L_o - original gauge length
- L_c - parallel length
- L_t - total length of test piece
- L_u - final gauge length after fracture
- d_o - original diameter of the parallel length of a circular test piece, or diameter of round wire or internal diameter of a tube

4.2 Charpy test samples

Samples were machined in accordance with standard ISO 148-1 “Metallic materials — Charpy pendulum impact test —Part 1: Test method”, article 6.

The standard test piece shall be 55 mm long and of square section, with 10 mm sides. In the center of the length, there shall be either a V-notch. If the standard test piece cannot be obtained from the material, one of the subsidiary test pieces, having a width of 7,5 mm, 5 mm or 2,5 mm, shall be used. The V-notch shall have an included angle of 45°, a depth of 2 mm, and a root radius of 0,25 mm.

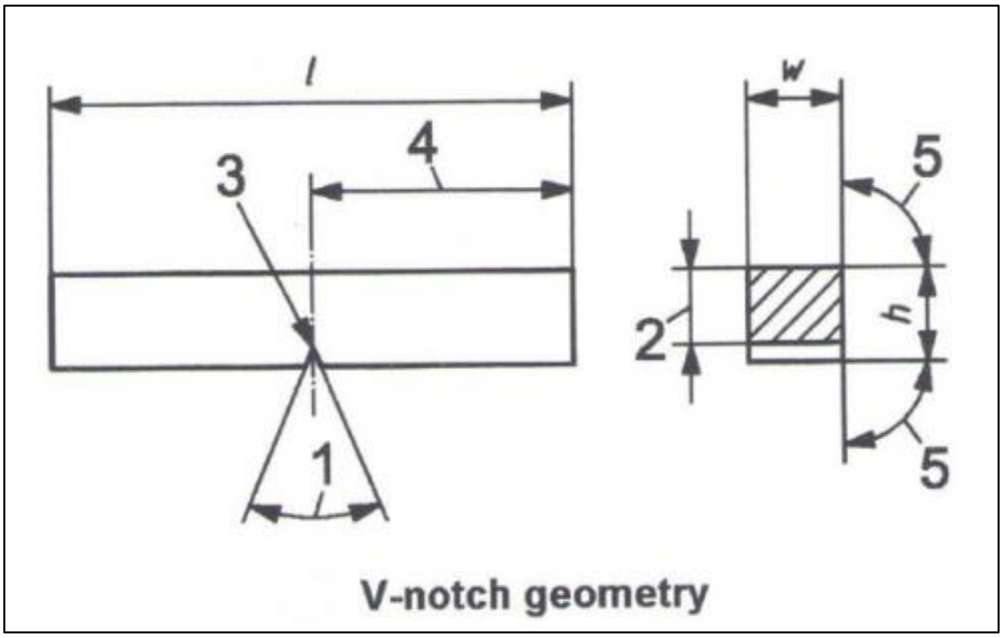


Figure 5: Shape and dimensions of Charpy test samples

4.3 Hardness test samples

Samples were machined in accordance with standard ISO 6507-1 “Metallic materials -- Vickers hardness test -- Part 1: Test method”, article 6.

The test shall be carried out on a surface which is smooth and even, free from oxide scale, foreign matter and, in particular, completely free from lubricants, unless otherwise specified in product standards. The finish of the surface shall permit accurate determination of the diagonal length of the indentation.

Preparation shall be carried out in such a way that any alteration of the surface hardness, due to excessive heating or cold-working, for example, is minimized.

Due to the small depth of Vickers micro hardness indentations, it is essential that special precautions are taken during preparation. It is recommended to use a polishing/electro polishing process which is suitable for the material parameters.

The thickness of the test piece, or of the layer under test, shall be at least 1,5 times the diagonal length of the indentation. No deformation shall be visible at the back of the test piece after the test.

4.4 Fracture toughness samples

Samples were machined in accordance with standard ISO 15653 "Metallic materials - Method of test for the determination of quasistatic fracture toughness".

The samples were machined so that the body surface material is not affected by technological operations.

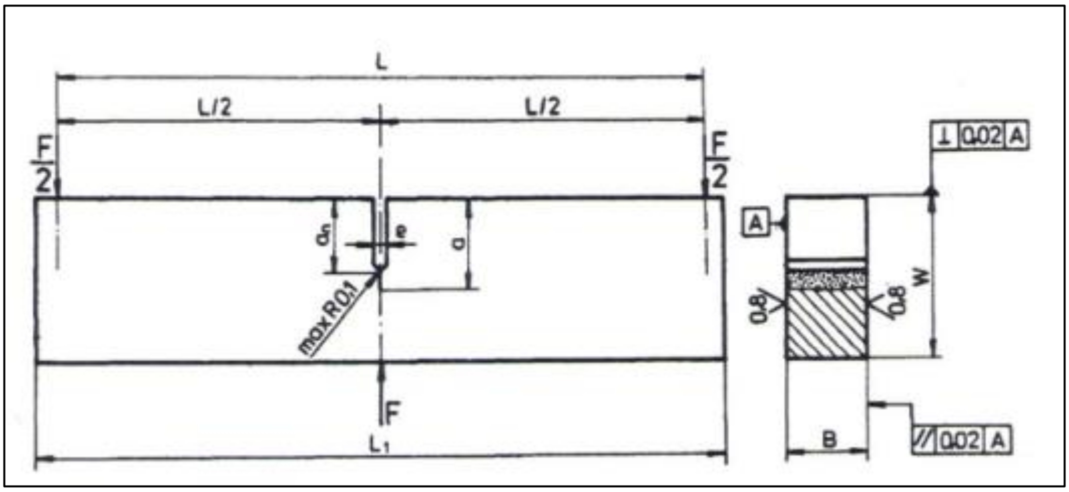


Figure 6: Shape and dimensions of fracture toughness samples

Table 5: Dimensions of samples

Dimension	B	W	a_{max}	a_n	e_{max}	L	L_{1min}
10	10	20	13	8	2,5	80	90
25	*25*	50	30	24	3,0	200	210
50	50	100	60	48	4,0	400	420
75	75	150	90	72	4,0	600	630
100	100	200	120	97	5,0	800	840
In general	0,5 W	W	(0,45-0,65)	0,48 W	0,025 W	4 W	4,2 W
Tolerance	±0,01 W	±0,005 W	-	-	-	±0,2 W	-

4.4.1 Samples for fatigue material tests

Samples for fatigue material test were machined in the same way as samples for tensile test (Figure 4).

4.5 Requirements

Prior to start of dynamic and braking tests, one DRFB disc, from each prototype, was randomly chosen for taking samples for destructive material tests, and test samples were made from this disc according to particular standards.

Results of these tests were then compared to required values stated on material certificates in production documentation for material EN-GJL-250 of DRFB disc crown, and C45E+QT for material of DRFB disc hub.

Table 6: Required values

Product	Material	$R_{p0,2}$	R_m	A	K_v	Hardness test
		[MPa]	[MPa]	[%]	[J]	[HBW]
disc	EN-GJL-250	-	250-350	-	-	190-240
hub	C45E+QT	min. 370	630-780	min. 17	32	187-235

5 1ST PROTOTYPE LABORATORY TESTS

5.1 1st prototype mechanical tests

5.1.1 Tensile test

Three samples for destructive tests were prepared. Test samples were made according to standard EN ISO 6892-1 Metallic materials - Tensile testing - Part 1: Method of test at room temperature. Results of these tests were compared with values stated on material certificates and material norms of production documentation for material EN-GJL-250 and C45E+QT.

Figure 7: Tensile test machined samples

Figure 8: Tensile test procedure

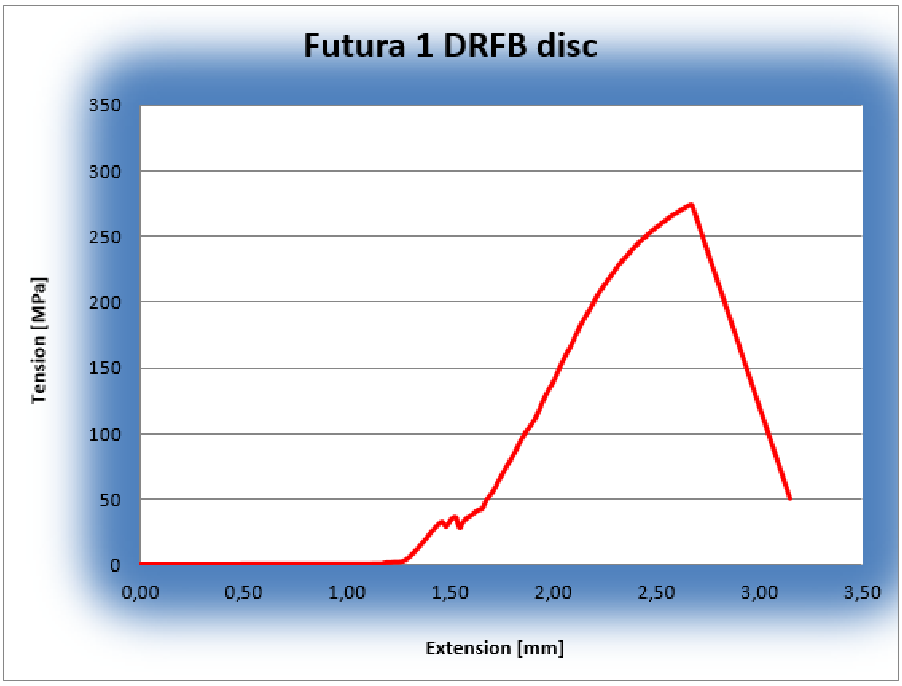


Figure 9: Graphic progress of 1st prototype DRFB disc crown tensile test

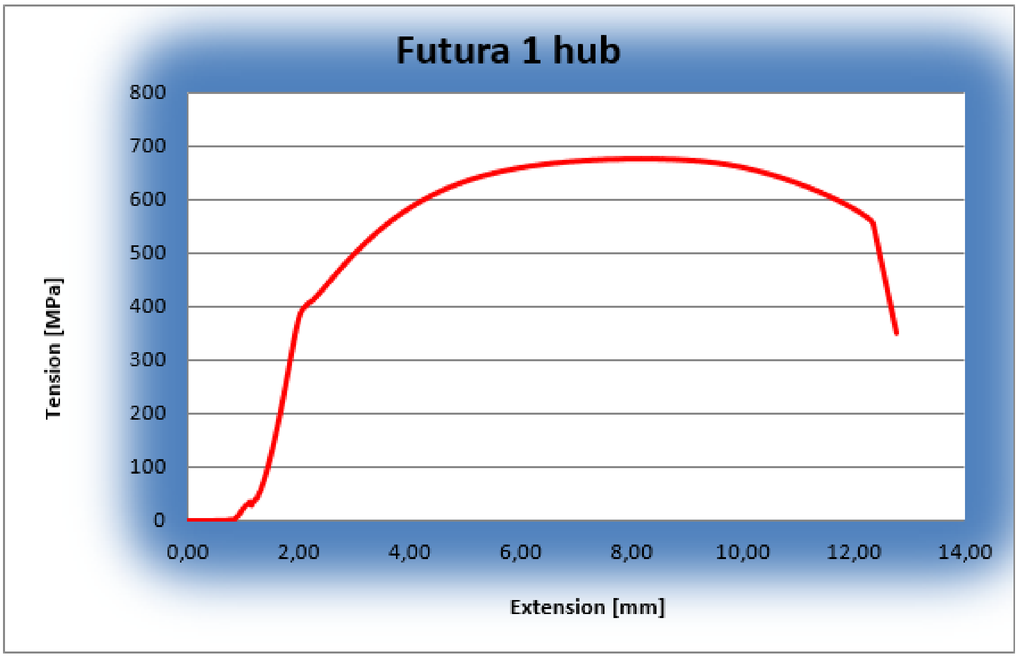


Figure 10: Graphic progress of 1st prototype DRFB disc hub tensile test

- 1st prototype results

All measured values of 1st prototype tests met given requirements. Results and requirements can be seen in the table below:

Table 7: 1st prototype tensile test results

No. of sample	Required values			Measured values (average)*			Result
	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	
DRFB disc crown	-	250-350	-	-	270	-	compliant
DRFB disc hub	min. 370	630-780	min. 17	405	686	22	compliant

5.1.2 Hardness test

Hardness tests were performed according to EN ISO 6506-1 “Metallic materials - Brinell hardness test - Part 1: Test method”.

Figure 11: Hardness test process

- 1^{st} prototype results

All measured values of 1^{st} prototype tests met given requirements. Results and requirements can be seen in the table below:

Table 8: 1^{st} prototype hardness test results

No. of sample	Required values	Measured values (average)*	Result
	Hardness [HBW]	Hardness [HBW]	
DRFB disc crown	190-240	199	satisfied
DRFB disc hub	187-235	200	satisfied

5.1.3 Fatigue material test

Fatigue material tests were performed according to STN 42 0363 "Metal testing. Fatigue testing of metals. Methodology of testing", and ISO 12107 "Metallic materials - Fatigue testing - Statistical planning and analysis of data".

The objective of the test was to prove endurance strength at sample with non-modified (not grinded) surface of sample at level of stress δu= 114 MPa. Sample of material was loaded with cyclic loading force with sinusoidal course, and maximum amplitude which loads sample with stress above 114 MPa.

In case of crack stress is lowered, and the test are repeated. According to mentioned standards there can't occur a crack after completing 2 millions of loading cycles with maximum stress higher than 114 MPa. Verification of surface crack is performed by non-destructive capillary control of surface defects on test sample. Positive test result will be confirmed between fatigue tests of two samples.

Figure 12: Fatigue material test sample

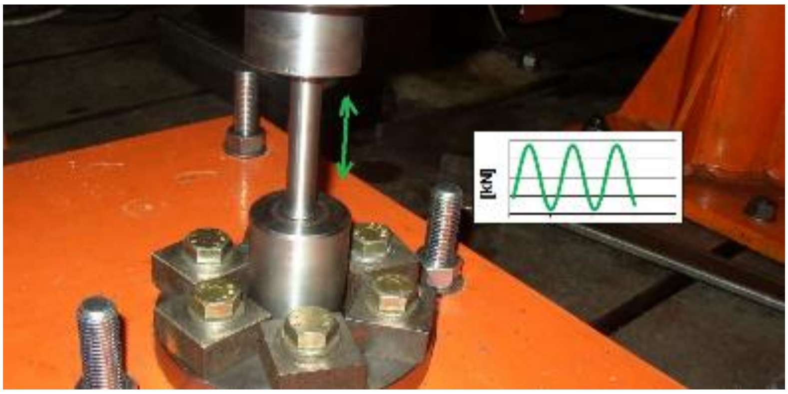


Figure 13: Fatigue test process

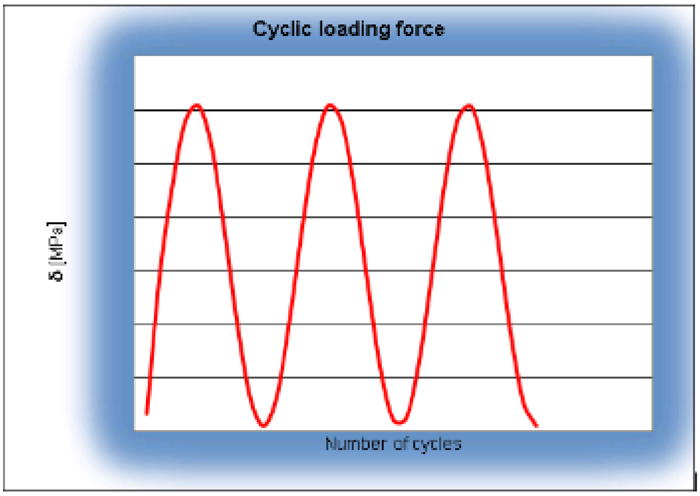


Figure 14: Graph of cyclic loading force

- 1st prototype results

All measured values of 1st prototype tests met given requirements. Results and requirements can be seen in the table below:

Table 9: 1st prototype fatigue test results

No. of sample	Material	Required level of fatigue stress δu [MPa]	Level of stress without cracks 2 samples [MPa]
DRFB disc hub	C45E+QT	min. 114	220

5.1.4 Charpy test

Charpy impact tests are performed according to EN ISO 148-1 “Metallic materials - Charpy pendulum impact test - Part 1: Test method”.

Samples were prepared in accordance with standard EN ISO 148-1. Notch geometry “V” was used for preparation of samples. The V-notch had an included angle of 45°, depth of 2 mm, and a root radius of 0,25 mm.

Figure 15: Charpy test samples

- 1st prototype results

All measured values of 1st prototype tests met given requirements, and are within required range. Results and requirements can be seen in the table below:

Table 10: 1st prototype Charpy test results

No. of sample	Required values	Measured values (average)*	Result
	K_v [J]	K_v [J]	
DRFB disc hub	min 32	56	compliant

Figure 16: Charpy test machine

5.1.5 Fracture toughness test

Fracture toughness test were performed according to ISO 15653 “Metallic materials -- Method of test for the determination of quasistatic fracture toughness”. The objective of the test was to check resistance to fracture with test specimens already containing a crack.

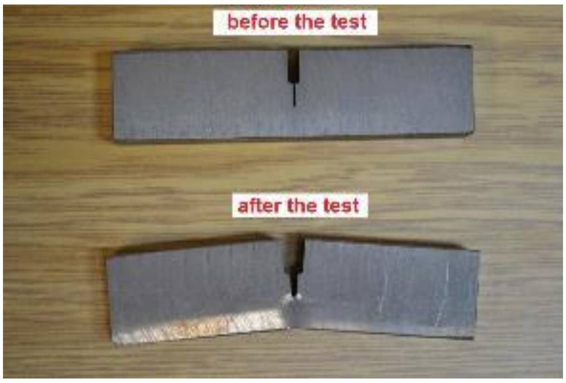


Figure 17: Fracture toughness test samples

Figure 18: Fracture toughness test process

- 1st prototype results

Results of 1st prototype fracture toughness tests of DRB disc and crown can be seen in the table below:

Table 11: 1st prototype fracture toughness test results

Load level	DRFB disc hub
	Force [kN]
F1	2,59
F2	4,82
F3	7,67

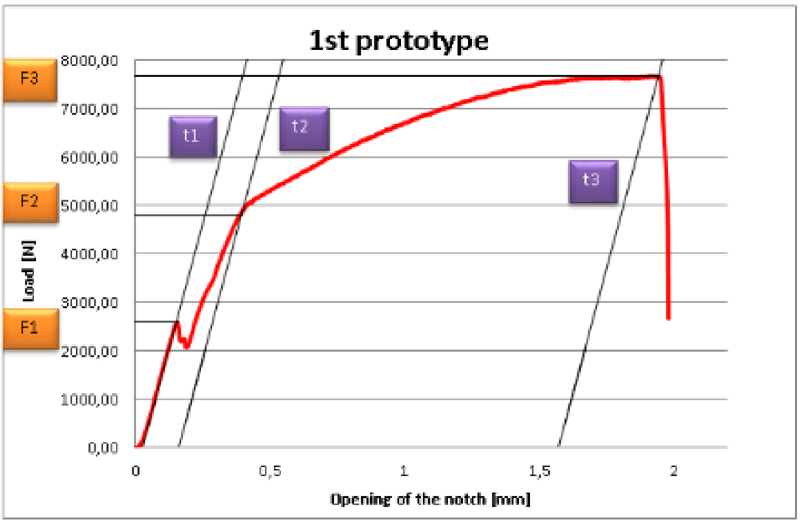


Figure 19: DRFB disc hub graphic fracture toughness progress

Figure 20: DRFB disc crown graphic fracture toughness progress

Table 12: 1st prototype fracture toughness test results

No. of sample	Required values according to EN 1561 – Annex A	Measured values
	K_{Ic} [MPa.m$^{1/2}$]	K_{Ic} [MPa.m$^{1/2}$]
1	17-20	19
2	17-20	19.5

5.2 1st prototype dynamical tests

Dynamical tests were performed on special dynamometric test bench for DRFB disc with maximum speed of 160 km/h, in order to check frictional, thermal, noise, and other properties of DRFB disc. The scope of tests was carefully chosen, and these tests were absolutely needed to confirm computer numerical calculations and to check performance of the disc.

Figure 21: DRFB disc test bench

These tests were:

- Local noise measurements during braking
- Local noise measurements (unbraked, while rotating the DRFB disc at certain speeds)
- Temperature measurements by PT100 and PT1000 thermocouples at different positions on DRFB disc crown and hub during single and multiple braking
- Vibrations measurements (Imbalance measurements)
- Coefficient of friction measurements between the DRFB disc and braking pads at different velocities
- Coefficient of friction measurements between the DRFB disc and braking pads at material degradation (corrosion, dust, humidity, wet conditions)
- Ventilation tests (power losses)
- Measuring the wear and volume of material at single and multiple braking, determining the mass (grams) and the volume of used material (cm3/MJ)

5.2.1 Local noise measurements during braking

Noise level measurements during braking were conducted during the UIC test program2A2. The microphone was positioned at 1m distance from the friction face of tested disc, and in the direction of the dynamometer axle and at the level of it.

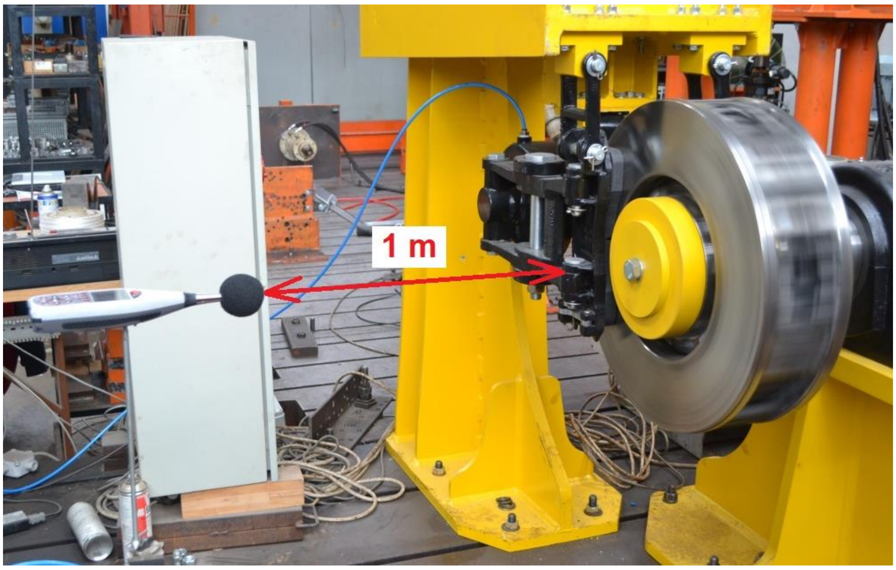


Figure 22: Position of microphone on test bench

As it can be seen from the table below, the highest level of noise of 92 dBA was during the 18th braking. The result was not compliant to requirement of max. 90 dBA.

Table 13: 1st prototype noise level at braking

Braking nr.	Noise [dBA]	Initial speed [km/h]	Fb [kN]	Avg. friction coef.	Max. Temp.
18	92	80	14	0,373	99

5.2.2 Local noise measurements (unbraked disc)

The noise generation test is performed in order to ensure that a brake disc under rotation does not produce a noise over the acceptance limit. Noise generation test was made in accordance with deliverable D1.1, section 6.7. The noise (sound pressure level in dBA generated by the rotation of the disc was measured at the speed 160 km/h with a microphone. The microphone was positioned at 1 m distance from the friction face of the tested disc in the direction of the dynamometer axle and at the level of it.

The measurement of noise was conducted at maximum speed of 160 km/h until a steady state of speed was reached. Then the noise was recorded for two minutes.

As a result of noise measurement, first prototype had value of 52 dBA, which is the lower value than prescribed in D1.1, section 6.7.1.

Table 14: 1st prototype noise test results

	Measured value	Requirement
	dBA	dBA
1st prototype	52	60

5.2.3 Temperature measurements at different positions on DRFB disc crown and hub during single and multiple braking

Temperature measurements were conducted for several tests for all DRFB discs prototypes. These tests were performed according requirement described in D1.1. The scope of tests was:

- Test of frictional characteristic (Test program 2A2 from UIC 541-3 with modified speed to 160 km/h).
- Heat dissipation test (Drag brake)
- DB – 175 Regulated braking (Thermal shock resistance)

The DRFB brake discs were equipped with six temperature sensors positioned 1 mm below the friction surface, three on each face. For each face, one sensor is on the middle radius of the friction face of brake ring and the other two are on the middle radius ± 40 mm, circumferentially positioned with 120° of angle each other.

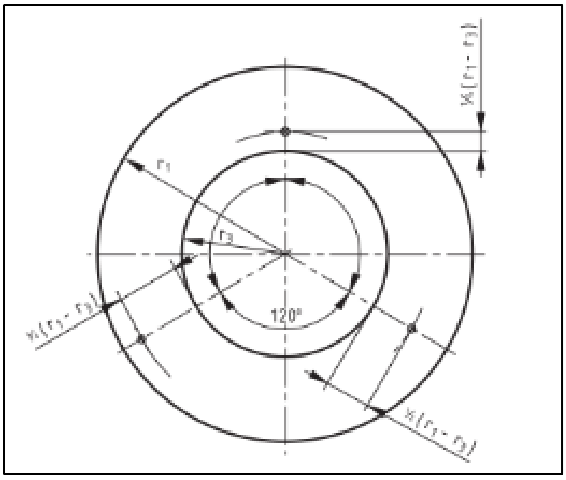


Figure 23: Position of temperature sensors

Figure 24: DRFB disc during the test

5.2.3.1 Test program 2A2 from UIC 541-3 with modified speed to 160 km/h.

Result temperatures from 2A2 test can be seen from picture below. As for 2A2 program, highest temperature was 402°C.

Temperatures from 2A2 program were not compliant to requirement of 375°C, which was requirement from report D1.1.

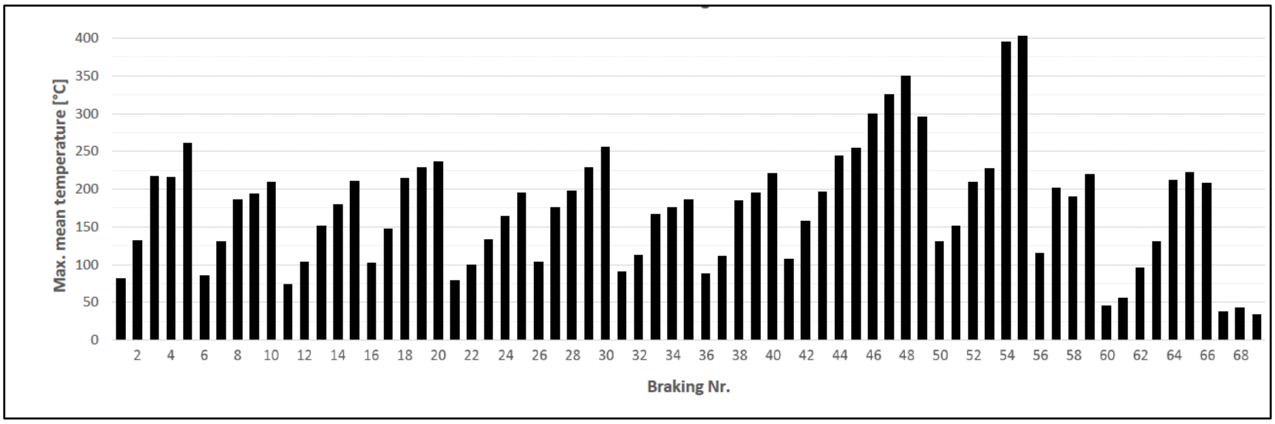


Figure 25: Temperatures of disc during 2A2 test program

5.2.3.2 **Heat dissipation tests (Drag brake)**

The purpose of the heat dissipation test was to qualify the thermal performance of the brake disc. So, the interest was to see the temperature and status of the discs after conducted tests at different power levels. The heat dissipation test was done according requirements described in D1.1. The results are presented below.

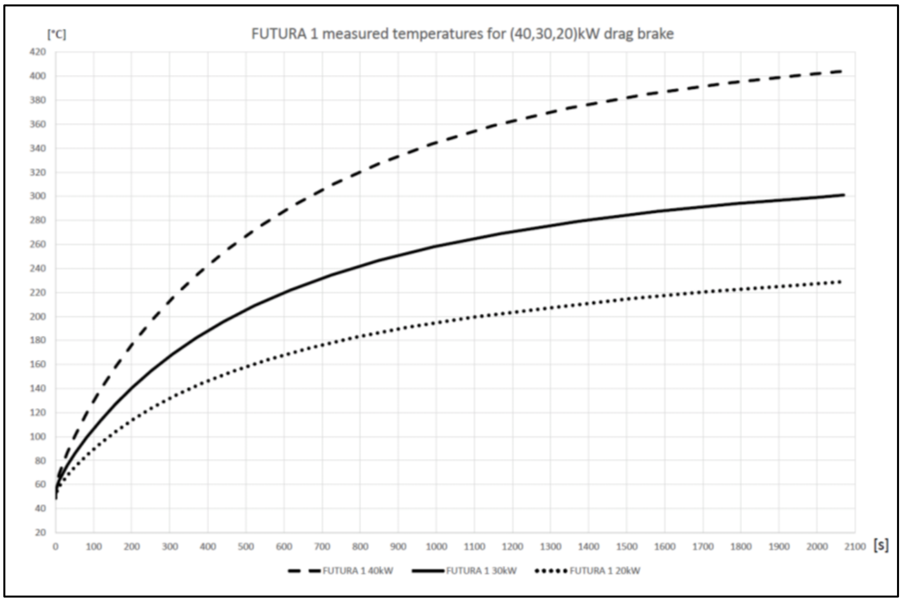


Figure 26: Temperatures of disc during heat dissipation test

Heat dissipation test at different power levels had temperatures from 231°C to 402°C, which is compliant to requirement of 450°C.

5.2.3.3 **DB – 175 Regulated braking (Thermal shock resistance)**

Program DB-175 is a program to verify thermal shock resistance against surface condition of the DRFB disc. This program consists of 175 braking from high velocity of 160 km/h to lower velocity of 80 km/h.

In this program, temperature is monitored and different conditions of the disc, like surface cracks and imbalance value were evaluated. Results of DB-175 test are presented below.

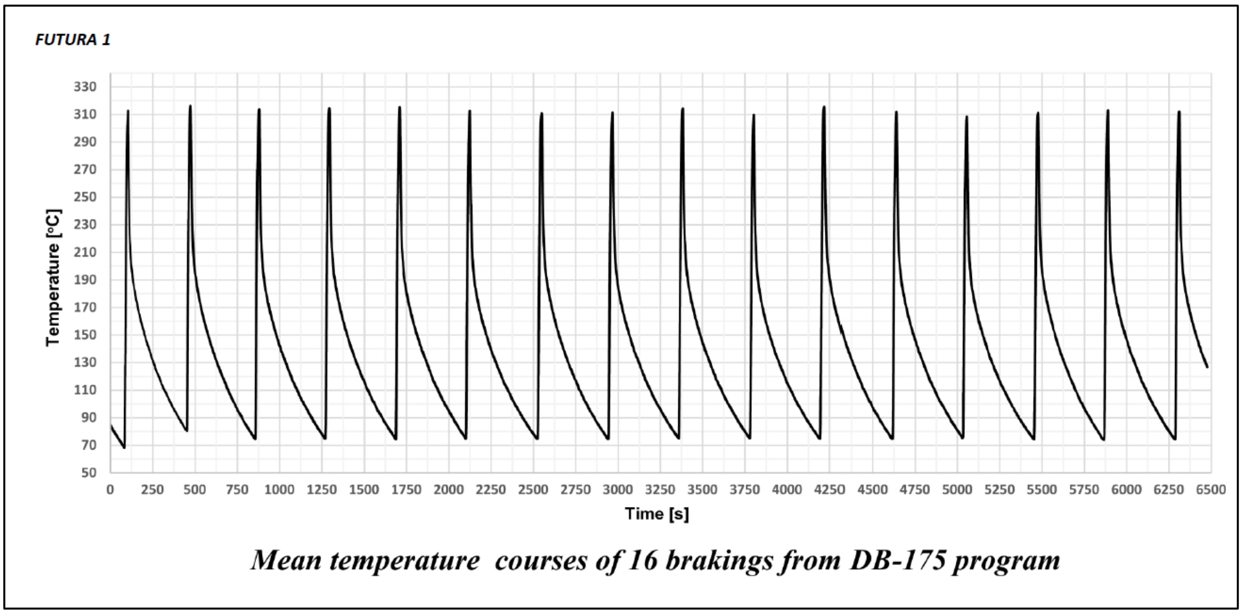


Figure 27: Temperatures of disc during DB-175 test

Result temperatures from DB-175 test can be seen from picture above. Highest temperature was 316°C, and on surface of the disc friction surface, there were some small surface cracks. These cracks were at the limit as prescribed in the maintenance manuals.

Figure 28: Disc after DB-175 program

5.2.4 Vibrations measurements

In order to check vibrations caused by possible radial movement of the DRFB disc crown, there was a requirement for checking the imbalance value of the disc prior and after the heat dissipation test and 175 braking test. Imbalance value was checked on special disc balancing machine.

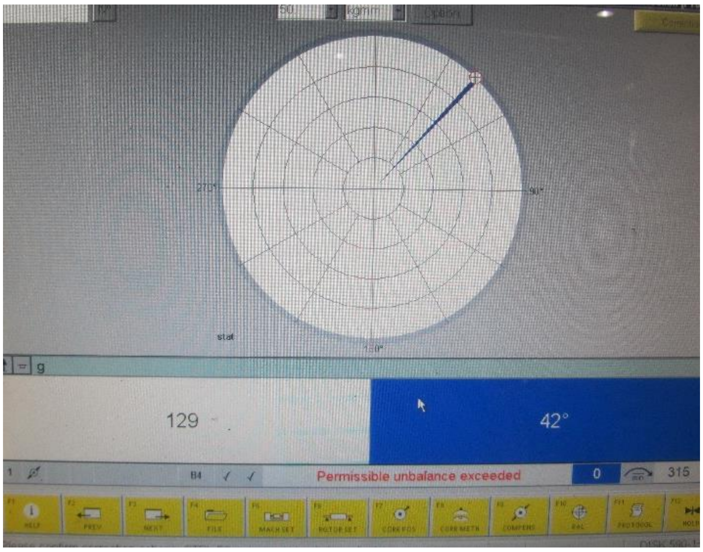


Figure 29: Special balancing machine

According to requirements, the imbalance value after test cannot exceed the value measured before test by more than 20%. As a result, after tests, first prototype had unallowable imbalance value. Result is presented in the table below:

Table 15: Vibration measurements

	Measured value [gm]	Value before test [gm]	Allowable value 20%
1st prototype	38	15	250%

5.2.5 Coefficient of friction measurements between the DRFB disc and braking pads at different velocities and material degradation (corrosion, humidity, wet conditions)

Measurements of friction coefficient at different velocities, while simulating different weather condition, such as dry and wet condition at temperatures between 10°C and 30°C, as well as material degradation (corrosion, dust) were conducted within UIC program 2A2.

The coefficient of friction was measured throughout all program 2A2 for both dry and wet condition. The wet conditions were simulated with wetting device mounted on the test bench. The quantity of water during the wet braking was 21 litter per hour.

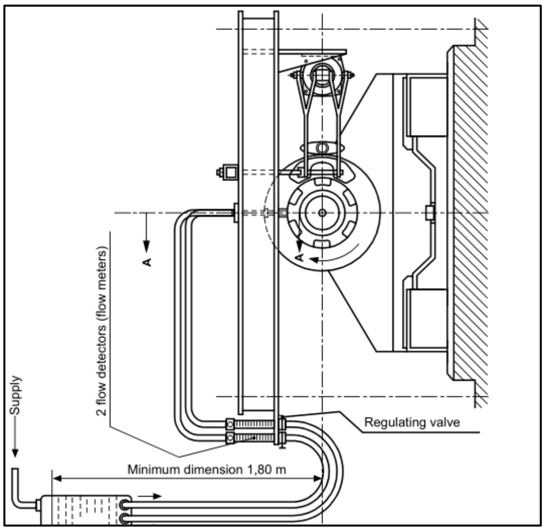


Figure 30: Wetting device

Braking at wet conditions created a layer of corrosion on the surface of the disc, and after drying, the disc collected dust from the braking pads degraded material. Then, the test continued in dry condition.

In this way, the coefficient of friction while simulating different weather conditions and degradation of material could be measured.

The coefficient of friction, during the dry and wet braking for can be seen on picture below.

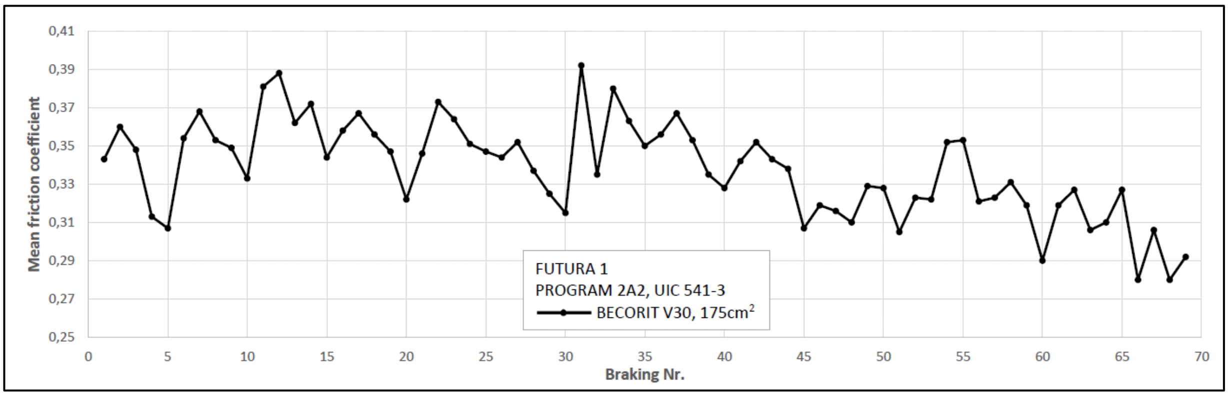


Figure 31: Friction coefficient of 1st prototype (Program 2A2)

5.2.6 Ventilation test (power losses)

The scope of the ventilation test was to evaluate and classify the ventilation losses generated by the disc during its rotation.

In this test, the aerodynamics of the DRFB disc can be seen, or, in another words, how much power is needed to keep the disc rotating at the constant speed. Ventilation properties of DRFB disc 1st prototype were measured at 160 km/h and at 80 km/h.

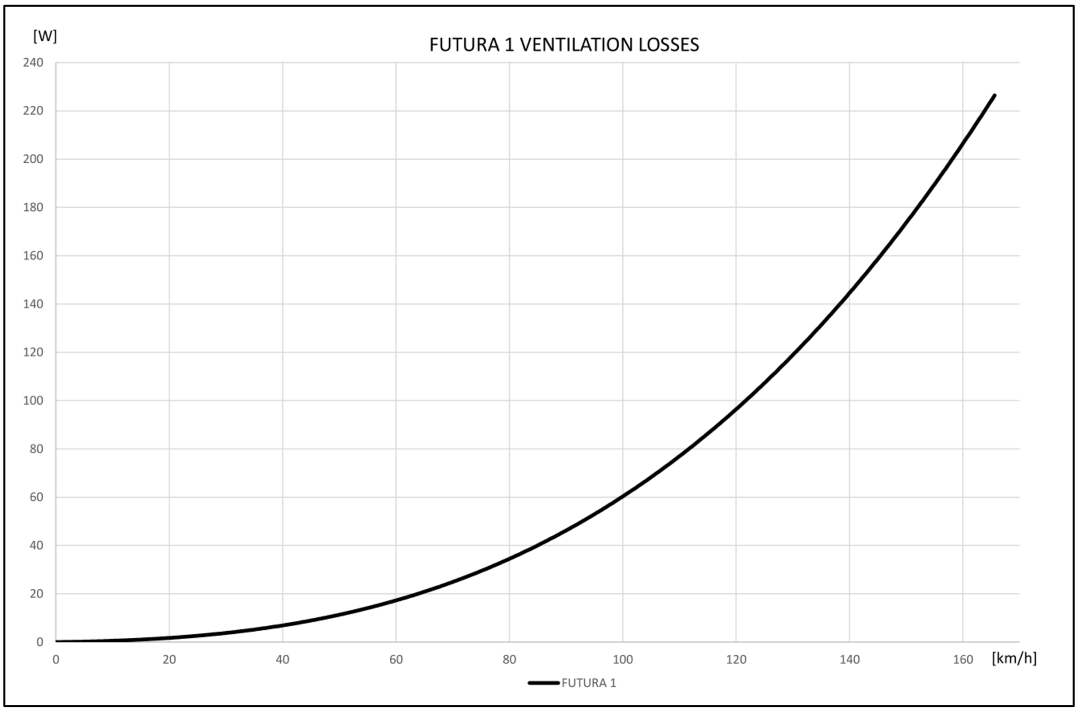


Figure 32: Ventilation losses for 1st prototype

For first prototype maximum ventilation losses were 206 W at speed 160 km/h, which is compliant to requirement of 350W.

5.2.7 Measurement of the wear of material (determining the mass and the volume of used material)

As prescribed in 2A2 program of UIC 541-3 standard, the wear of material (weighing) was done.

Figure 33: Brake pads after 2A2 test

The weighing of pads was done after bedding-in, 41st, 45th and 57th braking. The total loss of mass, during the 2A2 program was 151 grams. As specific weight of the pad is around 2.18 g/cm3 and the spent energy was 253,45 MJ, the specific volume of wear after the test was 0,273 cm3/MJ. This value is compliant to prescribed requirement of 0 ,28 cm^3.

Table 16: 1st prototype pad wear

State after Nr. Of braking:	Mass [g]					Wear			
	1	2	3	4	Σ 1-4	[g]	$[cm^3]$ (ρ = 2,18) [g/cm^3]	$[cm^3/MJ]$	Energy per interval [MJ]
R80	1084	1086	1068	1056	4294	45	20,64		
41	1062	1063	1047	1034	4206	43	19,72	0,12	165,34
45	1055	1057	1042	1029	4183	23	10,55	0,20	53,12
57	1044	1046	1033	1020	4143	40	18,35	0,52	34,98
					Σ=	151	69,27	0,273	253,45

6 2ND PROTOTYPE LABORATORY TESTS

6.1 2nd prototype mechanical tests

6.1.1 Tensile test

For second prototype, three samples for destructive tests were prepared. Test samples were made according to standard EN ISO 6892-1 Metallic materials - Tensile testing - Part 1: Method of test at room temperature. Results of these tests were compared with values stated on material certificates and material norms of production documentation for material EN-GJL-250 and C45E+QT.

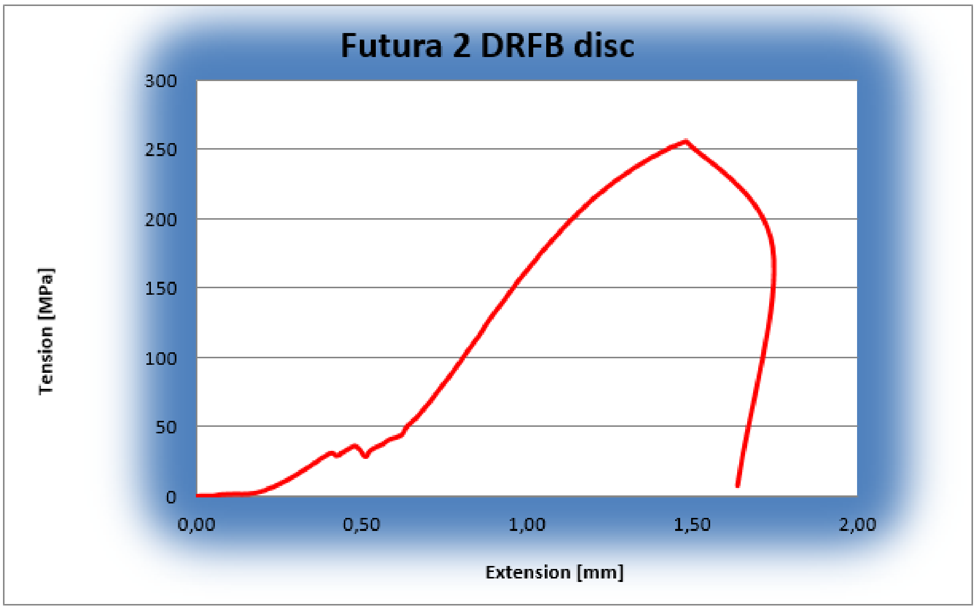


Figure 34: Graphic progress of 2nd prototype DRFB disc crown tensile test

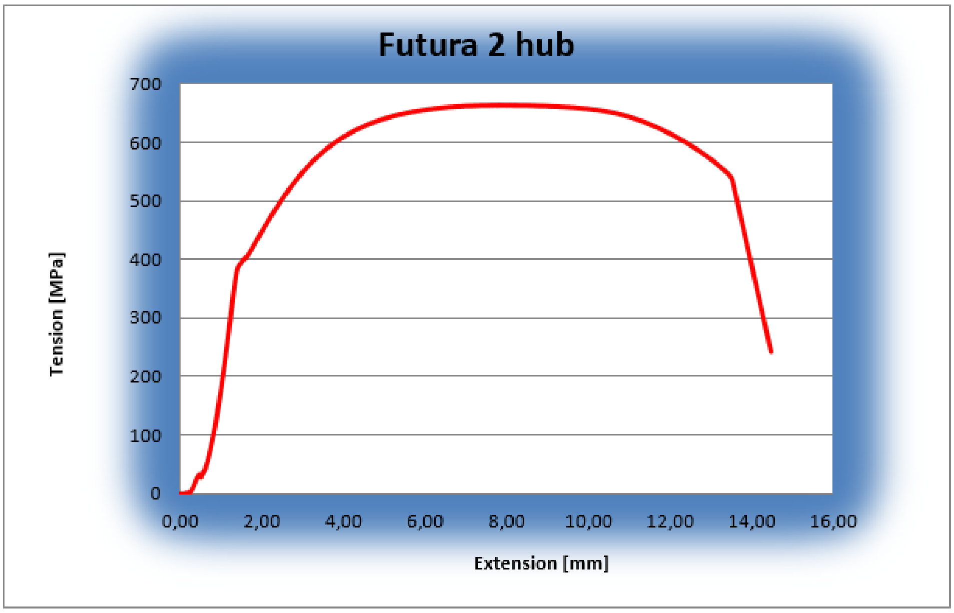


Figure 35: Graphic progress of 2nd prototype DRFB disc hub tensile test

- 2nd prototype results

All measured values of second prototype tests met given requirements. Results and requirements can be seen in the table below:

Table 17: 2nd prototype tensile test results

No. of sample	Required values			Measured values (average)*			Result
	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	
DRFB disc crown	-	250-350	-	-	256	-	compliant
DRFB disc hub	min. 370	630-780	min. 17	389	668	21	compliant

6.1.2 Hardness test

Hardness tests were performed according to EN ISO 6506-1 “Metallic materials - Brinell hardness test - Part 1: Test method”.

- 2nd prototype results

All measured values of second prototype tests met given requirements. Results and requirements can be seen in the table below:

Table 18: 2nd prototype hardness test results

No. of sample	Required values	Measured values (average)*	Result
	Hardness [HBW]	Hardness [HBW]	
DRFB disc crown	190-240	194	compliant
DRFB disc hub	187-235	202	compliant

6.1.3 Fatigue material test

Fatigue material tests were performed according to STN 42 0363 “Metal testing. Fatigue testing of metals. Methodology of testing”, and ISO 12107 “Metallic materials - Fatigue testing - Statistical planning and analysis of data”.

The objective of the test was to prove endurance strength at sample with non-modified (not grinded) surface of sample at level of stress δu= 114 MPa. Sample of material was loaded with cyclic loading force with sinusoidal course, and maximum amplitude which loads sample with stress above 114 MPa.

In case of crack stress is lowered, and the test are repeated. According to mentioned standards there can't occur a crack after completing 2 millions of loading cycles with maximum stress higher than 114 MPa. Verification of surface crack is performed by non-destructive capillary control of surface defects on test sample. Positive test result will be confirmed between fatigue tests of two samples. All measured values of second prototype tests met given requirements. Results and requirements can be seen in the table below:

Table 19: 2nd prototype fatigue test results

No. of sample	Material	Required level of fatigue stress δu [MPa]	Level of stress without cracks 2 samples [MPa]
DRFB disc hub	C45E+QT	min. 114	220

6.1.4 Charpy test

Charpy impact tests of second prototype were performed according to EN ISO 148-1 "Metallic materials - Charpy pendulum impact test - Part 1: Test method".

Samples were prepared in accordance with standard EN ISO 148-1. Notch geometry "V" was used for preparation of samples. The V-notch had an included angle of 45°, depth of 2 mm, and a root radius of 0,25 mm.

- 2nd prototype results

All measured values of second prototype tests met given requirements, and are within required range. Results and requirements can be seen in the table below:

Table 20: 2nd prototype Charpy test results

No. of sample	Required values	Measured values (average)*	Result
	K_v [J]	K_v [J]	
DRFB disc hub	min 32	47	compliant

Figure 36: Charpy test

6.1.5 Fracture toughness test

Fracture toughness test for second prototype were performed according to ISO 15653 “Metallic materials -- Method of test for the determination of quasistatic fracture toughness”. The objective of the test was to check resistance to fracture with test specimens already containing a crack.

Figure 37: Fracture toughness test samples

- 2nd prototype results

Results of second prototype fracture toughness tests of DRB disc and crown can be seen in the table below:

Table 21: 2nd prototype hub fracture toughness test results

Load level	DRFB disc hub
	Force [kN]
F1	2,41
F2	5,84
F3	7,66

F1 – fracture toughness at generation of first crack

F2 – fracture toughness at generation of second crack

F3 – maximum fracture toughness

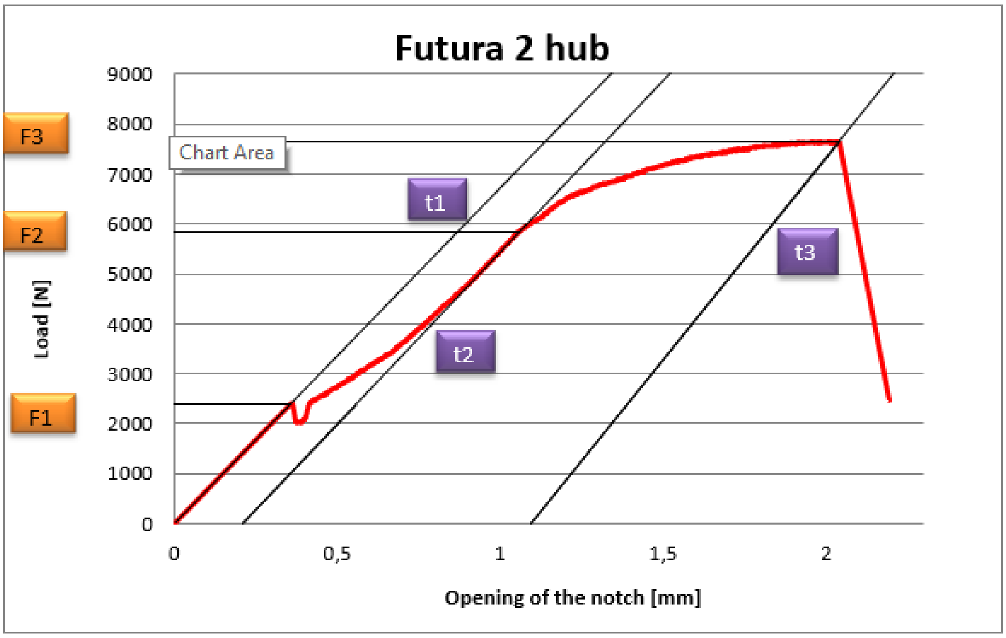


Figure 38: DRFB disc hub graphic fracture toughness test progress

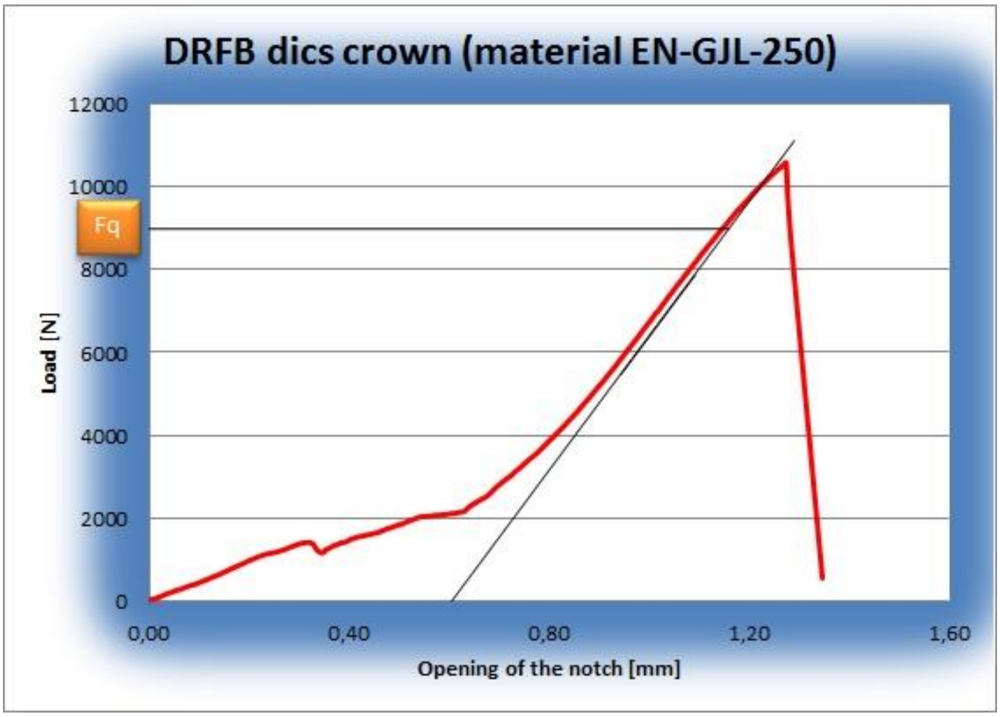


Figure 39: DRFB disc crown graphic fracture toughness progress

Table 22: 2nd prototype crown fracture toughness test results

No. of sample	Required values according to EN 1561 – Annex A	Measured values
	K_{Ic} [MPa.m$^{1/2}$]	K_{Ic} [MPa.m$^{1/2}$]
1	17-20	20,7
2	17-20	20,5

6.2 2nd prototype dynamical tests

Second prototype dynamical tests were performed on special dynamometric test bench for DRFB disc with maximum speed of 160 km/h, in order to check frictional, thermal, noise, and other properties of DRFB disc. The scope of tests was carefully chosen, and these tests were absolutely needed to confirm computer numerical calculations and to check performance of the disc.

Figure 40: 2nd prototype DRFB disc test

These tests were:

- Local noise measurements during braking
- Local noise measurements (unbraked, while rotating the DRFB disc at certain speeds)
- Temperature measurements by PT100 and PT1000 thermocouples at different positions on DRFB disc crown and hub during single and multiple braking
- Vibrations measurements (Imbalance measurements)
- Coefficient of friction measurements between the DRFB disc and braking pads at different velocities
- Coefficient of friction measurements between the DRFB disc and braking pads at material degradation (corrosion, dust, humidity, wet conditions)
- Ventilation tests (power losses)
- Measuring the wear and volume of material at single and multiple braking, determining the mass (grams) and the volume of used material (cm3/MJ)

6.2.1 Local noise measurements during braking

Noise level measurements during braking were conducted during the UIC test program2A2. The microphone was positioned at 1m distance from the friction face of tested disc, and in the direction of the dynamometer axle and at the level of it.

Figure 41: Noise test

As it can be seen from the table below, the highest level of noise of 93 dBA was during the 27th braking. The result was not compliant to requirement of max. 90 dBA.

Table 23: 2nd prototype noise level at braking

Braking nr.	Noise [dBA]	Initial speed [km/h]	Fb [kN]	Avg. friction coef.	Max. Temp.
27	93	120	27	0,353	196

6.2.2 Local noise measurements (unbraked disc)

The noise generation test is performed in order to ensure that a brake disc under rotation does not produce a noise over the acceptance limit. Noise generation test was made in accordance with deliverable D1.1, section 6.7. The noise (sound pressure level in dBA generated by the rotation of the disc was measured at the speed 160 km/h with a microphone. The microphone was positioned at 1 m distance from the friction face of the tested disc in the direction of the dynamometer axle and at the level of it.

The measurement of noise was conducted at maximum speed of 160 km/h until a steady state of speed was reached. Then the noise was recorded for two minutes.

As a result of noise measurement, second prototype had value of 56 dBA, which is compliant to requirement of 60 dBA prescribed in D1.1, section 6.7.1.

Table 24: 2nd prototype noise test results

	Measured value	Requirement
	dBA	dBA
2nd prototype	56	60

6.2.3 Temperature measurements at different positions on DRFB disc crown and hub during single and multiple braking

Temperature measurements were conducted for several tests for all DRFB discs prototypes. These tests were performed according requirement described in D1.1. The scope of tests was:

- Test of frictional characteristic (Test program 2A2 from UIC 541-3 with modified speed to 160 km/h).
- Heat dissipation test (Drag brake)
- DB – 175 Regulated braking (Thermal shock resistance)

The DRFB brake discs were equipped with six temperature sensors positioned 1 mm below the friction surface, three on each face. For each face, one sensor is on the middle radius of the friction face of brake ring and the other two are on the middle radius ± 40 mm, circumferentially positioned with 120° of angle each other.

6.2.3.1 Test program 2A2 from UIC 541-3 with modified speed to 160 km/h.

Result temperatures from second prototype 2A2 test can be seen from picture below. As for 2A2 program, highest temperature was 404°C.

Temperatures from 2A2 program were not compliant to requirement of 375°C, as prescribed in report D1.1.

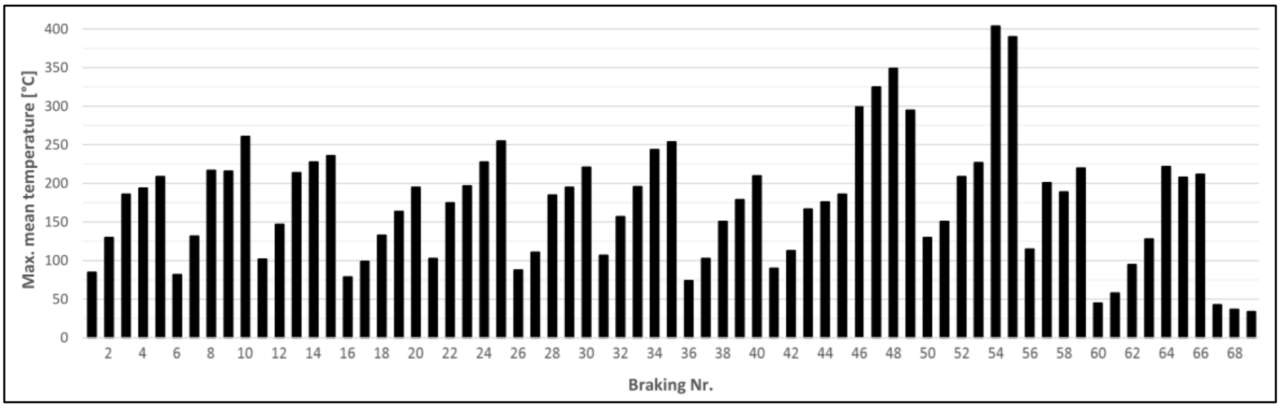


Figure 42: Temperatures of DRFB disc during 2A2 test program

6.2.3.2 Heat dissipation tests (Drag brake)

The purpose of the heat dissipation test was to qualify the thermal performance of the brake disc. So, the interest was to see the temperature and status of the discs after conducted tests at different power levels. The heat dissipation test of second prototype was done according requirements described in D1.1. The results are presented below.

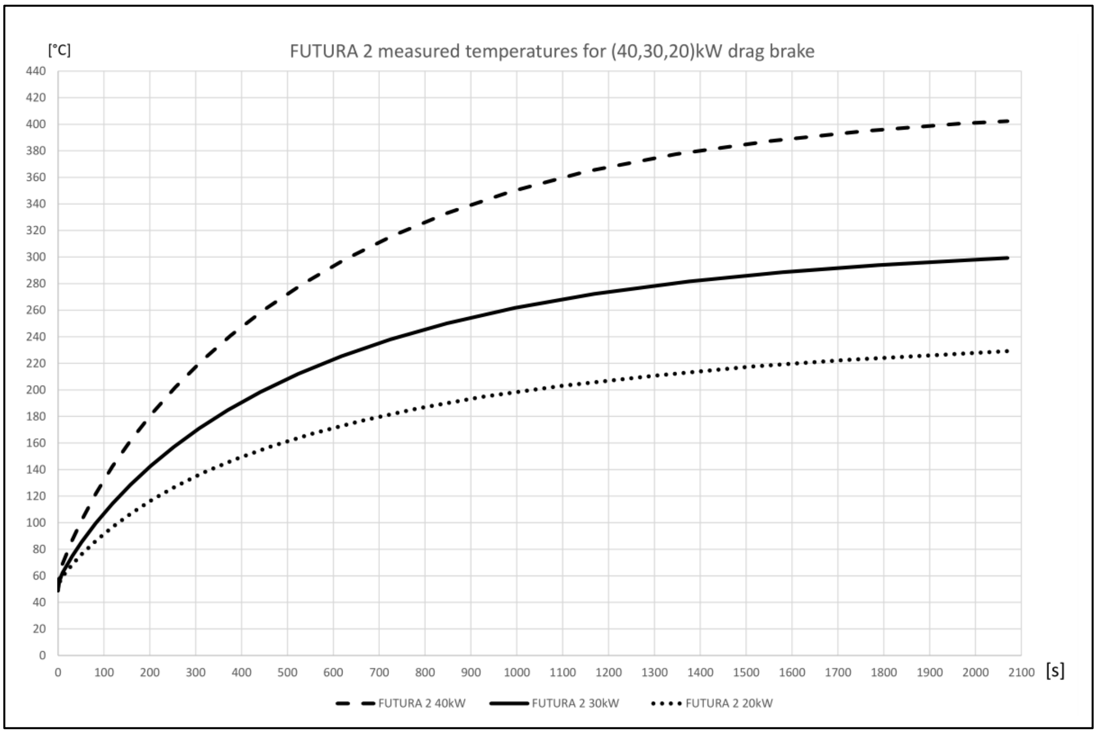


Figure 43: Temperatures of disc during heat dissipation test

Heat dissipation test temperatures at different power were from 230°C to 401°C, which is compliant to requirement of 450°C.

6.2.3.3 DB – 175 Regulated braking (Thermal shock resistance)

Program DB-175 is a program to verify thermal shock resistance against surface condition of the DRFB disc. This program consists of 175 braking from high velocity of 160 km/h to lower velocity of 80 km/h.

In this program, temperature is monitored and different conditions of the disc, like surface cracks and imbalance value were evaluated. Results of second prototype DB-175 test are presented below.

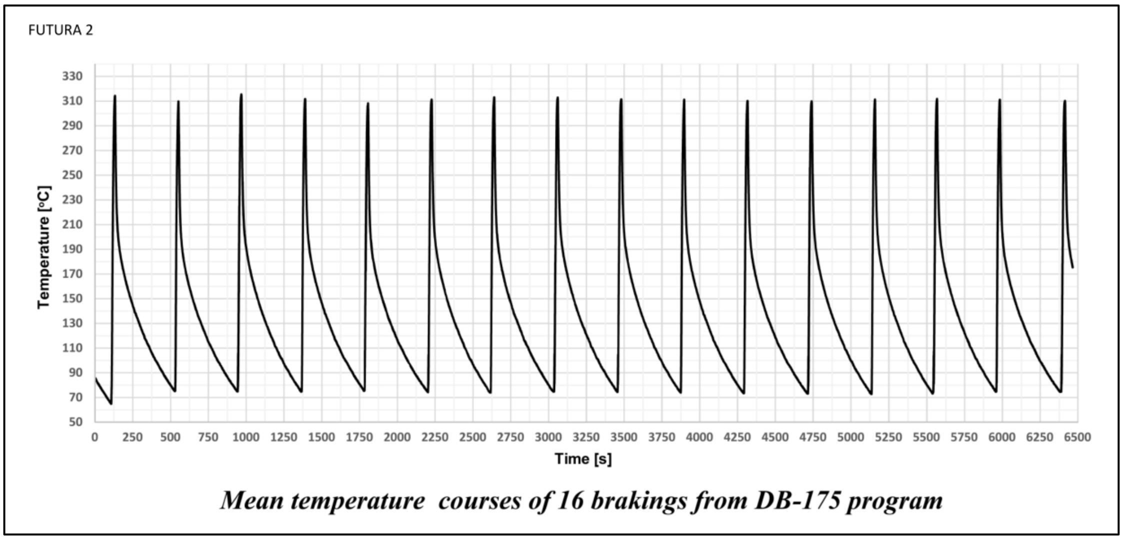


Figure 44: Temperatures of DRFB disc during DB-175 test

Result temperatures from DB-175 test can be seen from picture above. Highest temperature was 315°C, and on surface of the disc friction surface, there were some small surface cracks. These cracks were at the limit as prescribed in the maintenance manuals.

Figure 45: 2nd prototype after DB-175 program

6.2.4 Vibrations measurements

In order to check vibrations caused by possible radial movement of the DRFB disc crown, there was a requirement for checking the imbalance value of the disc prior and after the heat dissipation test and 175 braking test. Imbalance value was checked on special disc balancing machine.

Figure 46: 2nd prototype vibration measurement

According to requirements, the imbalance value after test cannot exceed the value measured before test by more than 20%. As a result, after tests, fi prototype had unallowable imbalance value. Result is presented in the table below:

Table 25: Vibration measurements

	Measured value	Value before test	Allowable value
	[gm]	[gm]	20%
2nd prototype	36	7	514%

6.2.5 Coefficient of friction measurements between the DRFB disc and braking pads at different velocities and material degradation (corrosion, humidity, wet conditions)

Second prototype measurements of friction coefficient at different velocities, while simulating different weather condition, such as dry and wet condition at temperatures between 10°C and 30°C, as well as material degradation (corrosion, dust) were conducted within UIC program 2A2.

The coefficient of friction was measured throughout all program 2A2 for both dry and wet condition. The wet conditions were simulated with wetting device mounted on the test bench. The quantity of water during the wet braking was 21 litter per hour.

Braking at wet conditions created a layer of corrosion on the surface of the disc, and after drying, the disc collected dust from the braking pads degraded material. Then, the test continued in dry condition.

In this way, the coefficient of friction while simulating different weather conditions and degradation of material could be measured.

The coefficient of friction, during the dry and wet braking for can be seen on picture below.

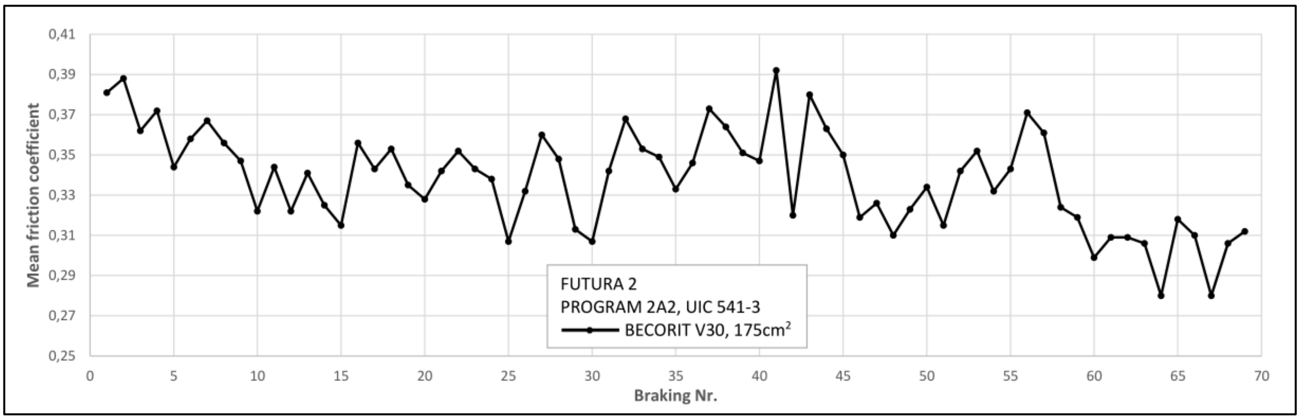


Figure 47: 2nd prototype friction coefficient (Program 2A2)

6.2.6 Ventilation test (power losses)

During this test, the aerodynamics of the DRFB disc can be seen, or, in another words, how much power is needed to keep the disc rotating at the constant speed. Ventilation properties of second prototype of DRFB disc were measured at 160 km/h and at 80 km/h.

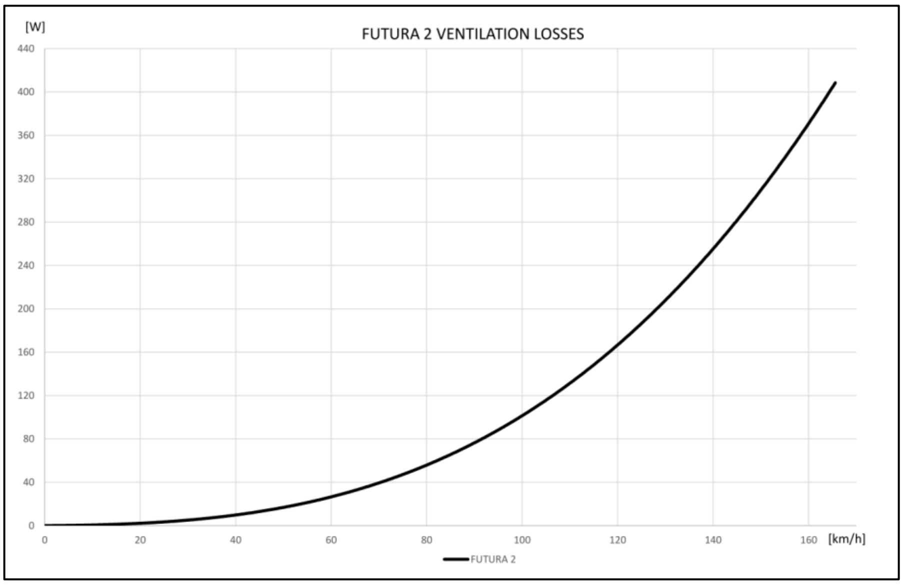


Figure 48: 2nd prototype ventilation losses

For second prototype maximum ventilation losses were 378 W at speed 160 km/h, which was not compliant to requirement of 350W.

6.2.7 Measurement of the wear of material (determining the mass and the volume of used material)

As prescribed in 2A2 program of UIC 541-3 standard, the wear of material (weighing) was done.

The weighing of pads was done after bedding-in, 41st, 45th and 57th braking. The total loss of mass, during the 2A2 program was 153 grams. As specific weight of the pad is around 2.18 g/cm3 and the spent energy was 254,81 MJ, the specific volume of wear after the test was 0,276 cm3/MJ. This value is compliant to prescribed requirement 0,28 cm^3.

Table 26: 2nd prototype pad wear

State after Nr. Of braking:	Mass [g]					Wear			
	1	2	3	4	Σ 1-4	[g]	$[cm^3]$ ($\rho = 2{,}18$) $[g/cm^3]$	$[cm^3/MJ]$	Energy per interval [MJ]
RBO	1069	1087	1082	1068	4306	44	20,06		
41	1064	1062	1068	1069	4263	43	19,81	0,12	166,43
45	1061	1058	1051	1052	4222	40	18,56	0,35	53,12
57	1052	1047	1042	1055	4196	26	11,90	0,34	35,26
					Σ=	153	70,33	0,276	254,81

7 3RD PROTOTYPE LABORATORY TESTS

7.1 3rd prototype mechanical tests

7.1.1 Tensile test

Followed by second prototype tensile tests, three samples of third prototype were prepared for destructive tests. Results of these tests were compared with values stated on material certificates and material norms of production documentation for material EN-GJL-250 and C45E+QT.

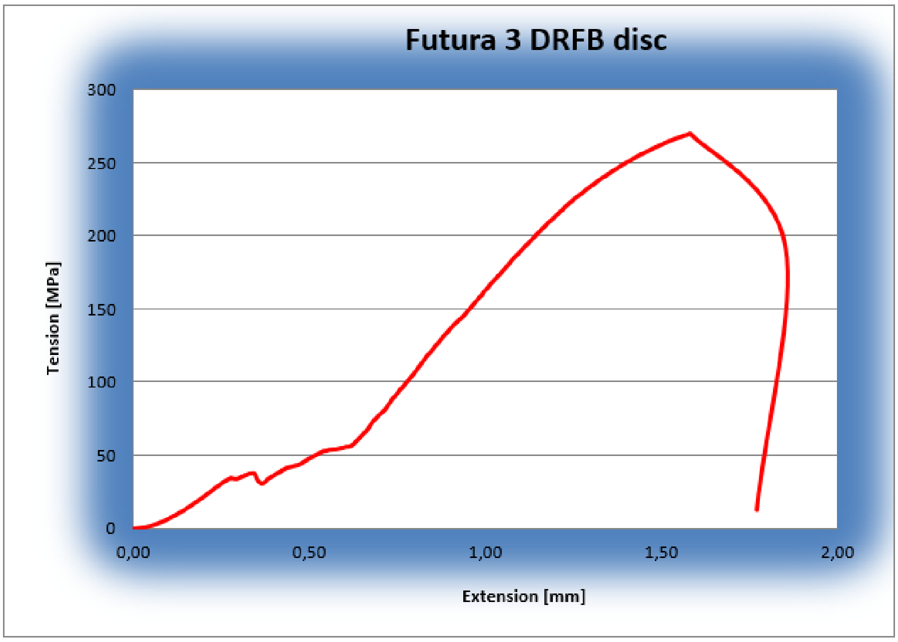


Figure 49: Graphic progress of 3rd prototype DRFB disc crown tensile test

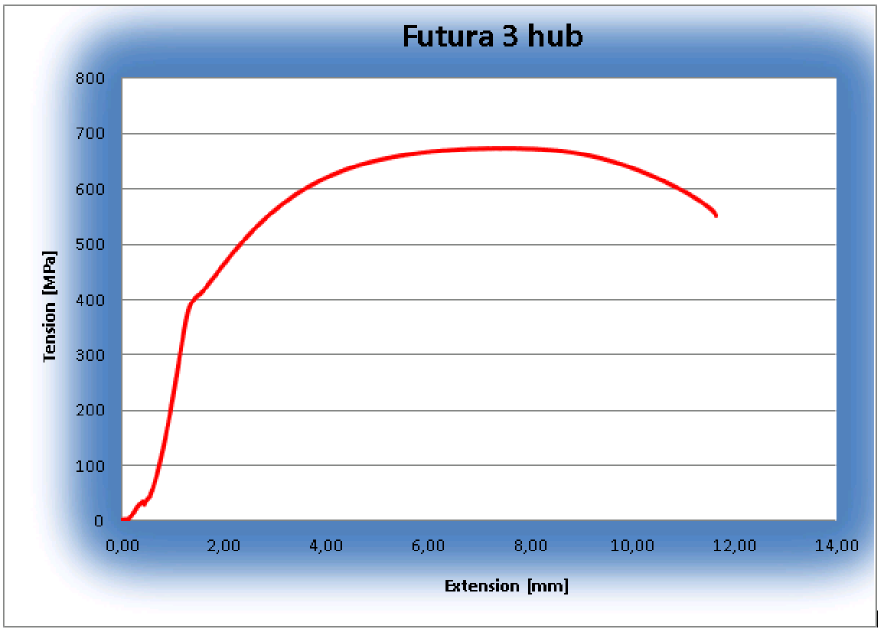


Figure 50: Graphic progress of 3rd prototype DRFB disc hub tensile test

- 3rd prototype results

All measured values of third prototype tests met given requirements. Results and requirements can be seen in the table below:

Table 27: 3rd prototype tensile test results

No. of sample	Required values			Measured values (average)*			Result
	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	
DRFB disc crown	-	250-350	-	-	270	-	compliant
DRFB disc hub	min. 370	630-780	min. 17	393	674	20	compliant

7.1.2 Hardness test

Hardness tests of third prototype were performed according to EN ISO 6506-1 "Metallic materials - Brinell hardness test - Part 1: Test method".

- 3rd prototype results

All measured values of third prototype tests met given requirements. Results and requirements can be seen in the table below:

Table 28: 3rd prototype hardness test results

No. of sample	Required values	Measured values (average)*	Result
	Hardness [HBW]	Hardness [HBW]	
DRFB disc crown	190-240	198	compliant
DRFB disc hub	187-235	203	compliant

7.1.3 Fatigue material test

Fatigue material tests were performed according to STN 42 0363 "Metal testing. Fatigue testing of metals. Methodology of testing", and ISO 12107 "Metallic materials - Fatigue testing - Statistical planning and analysis of data".

The objective of the test was to prove endurance strength at sample with non-modified (not grinded) surface of sample at level of stress δu= 114 MPa. Sample of material was loaded with cyclic loading force with sinusoidal course, and maximum amplitude which loads sample with stress above 114 MPa.

In case of crack stress is lowered, and the test are repeated. According to mentioned standards there can't occur a crack after completing 2 million of loading cycles with maximum stress higher than 114 MPa. Verification of surface crack is performed by non-destructive capillary control of surface defects on test sample. Positive test result will be confirmed between fatigue tests of two samples. All measured values of third prototype tests met given requirements. Results and requirements can be seen in the table below:

Table 29: 3rd prototype fatigue test results

No. of sample	Material	Required level of fatigue stress δu [MPa]	Level of stress without cracks 2 samples [MPa]
DRFB disc hub	C45E+QT	min. 114	218

7.1.4 Charpy test

Charpy impact tests of third prototype were performed according to EN ISO 148-1 "Metallic materials - Charpy pendulum impact test - Part 1: Test method".

Samples were prepared in accordance with standard EN ISO 148-1. Notch geometry "V" was used for preparation of samples. The V-notch had an included angle of 45°, depth of 2 mm, and a root radius of 0,25 mm.

- 3rd prototype results

All measured values of third prototype tests met given requirements, and are within required range. Results and requirements can be seen in the table below:

Table 30: 3rd prototype Charpy test results

No. of sample	Required values	Measured values (average)*	Result
	K_v [J]	K_v [J]	
DRFB disc hub	min 32	43	compliant

7.1.5 Fracture toughness test

Fracture toughness test for third prototype were performed according to ISO 15653 “Metallic materials -- Method of test for the determination of quasistatic fracture toughness”. The objective of the test was to check resistance to fracture with test specimens already containing a crack.

- 3rd prototype results

Results of third prototype fracture toughness tests of DRB disc and crown can be seen in the table below:

Table 31: 3rd prototype hub fracture toughness test results

Load level	DRFB disc hub Force [kN]
F1	2,54
F2	6,04
F3	8,24

F1 – fracture toughness at generation of first crack

F2 – fracture toughness at generation of second crack

F3 – maximum fracture toughness

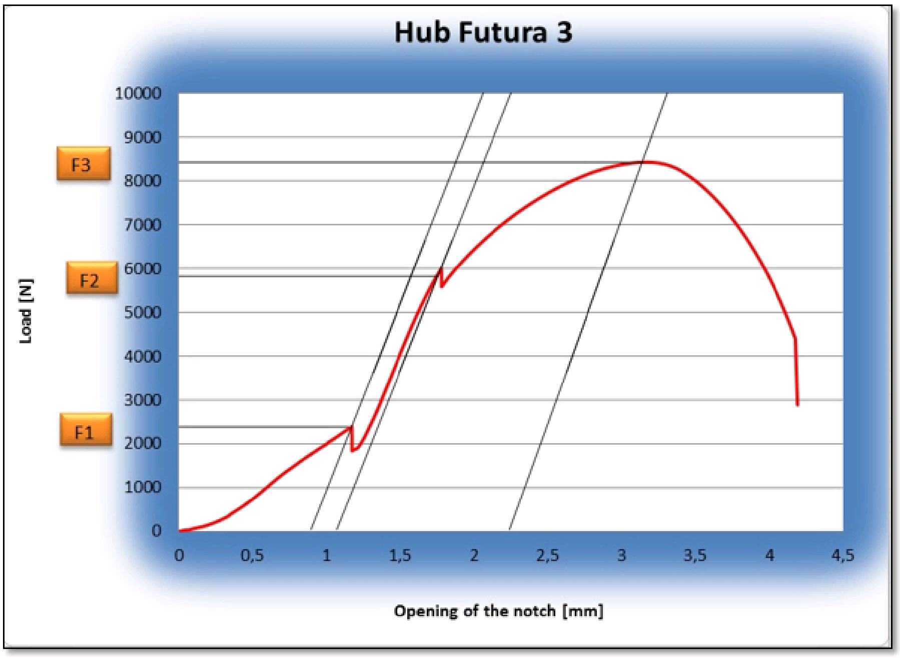


Figure 51: DRFB disc hub graphic fracture toughness test progress

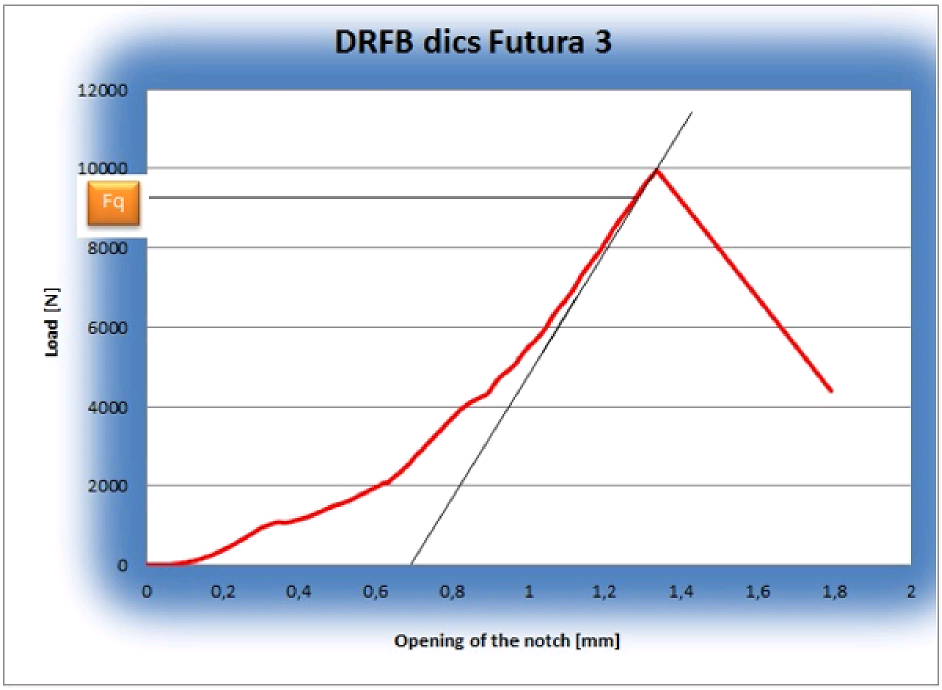


Figure 52: DRFB disc crown graphic fracture toughness progress

Table 32: 3rd prototype crown fracture toughness test results

No. of sample	Required values according to EN 1561 – Annex A	Measured values
	K_{Ic} [MPa.m$^{1/2}$]	K_{Ic} [MPa.m$^{1/2}$]
1	17-20	20,8
2	17-20	20,7

7.2 3rd prototype dynamical tests

Third prototype dynamical tests were performed on special dynamometric test bench for DRFB disc with maximum speed of 160 km/h, in order to check frictional, thermal, noise, and other properties of DRFB disc. The scope of tests was carefully chosen, and these tests were absolutely needed to confirm computer numerical calculations and to check performance of the disc.

Figure 53: 3rd prototype DRFB disc

These tests were:

- Local noise measurements during braking
- Local noise measurements (unbraked, while rotating the DRFB disc at certain speeds)
- Temperature measurements by PT100 and PT1000 thermocouples at different positions on DRFB disc crown and hub during single and multiple braking
- Vibrations measurements (Imbalance measurements)
- Coefficient of friction measurements between the DRFB disc and braking pads at different velocities
- Coefficient of friction measurements between the DRFB disc and braking pads at material degradation (corrosion, dust, humidity, wet conditions)
- Ventilation tests (power losses)
- Measuring the wear and volume of material at single and multiple braking, determining the mass (grams) and the volume of used material (cm3/MJ)

7.2.1 Local noise measurements during braking

Same as for previous prototypes, noise level measurements during braking were conducted on third one during the UIC test program2A2. The microphone was positioned at 1m distance from the friction face of tested disc, and in the direction of the dynamometer axle and at the level of it.

As it can be seen from the table below, the highest level of noise of 94 dBA was during the 24th braking. The result was not compliant to requirement of max. 90 dBA.

Table 33: 3rd prototype noise level at braking

Braking nr.	Noise [dBA]	Initial speed [km/h]	Fb [kN]	Avg. friction coef.	Max. Temp.
24	94	140	40	0,349	226

7.2.2 Local noise measurements (unbraked disc)

The noise generation test was performed in order to ensure that a brake disc under rotation does not produce a noise over the acceptance limit. Noise generation test was made in accordance with deliverable D1.1, section 6.7. The noise (sound pressure level in dBA generated by the rotation of the disc was measured at the speed 160 km/h with a microphone. The microphone was positioned at 1 m distance from the friction face of the tested disc in the direction of the dynamometer axle and at the level of it.

The measurement of noise was conducted at maximum speed of 160 km/h until a steady state of speed was reached. Then the noise was recorded for two minutes.

As a result of noise measurement, third prototype had value of 57 dBA, which was compliant to requirement of 60 dBA prescribed in D1.1, section 6.7.1.

Table 34: 3rd prototype noise test results

	Measured value	Requirement
	dBA	dBA
3rd prototype	57	60

7.2.3 Temperature measurements at different positions on DRFB disc crown and hub during single and multiple braking

Temperature measurements were conducted for several tests for all DRFB discs prototypes. These tests were performed according requirement described in D1.1. The scope of tests was:

- Test of frictional characteristic (Test program 2A2 from UIC 541-3 with modified speed to 160 km/h).
- Heat dissipation test (Drag brake)
- DB – 175 Regulated braking (Thermal shock resistance)

The DRFB brake discs were equipped with six temperature sensors positioned 1 mm below the friction surface, three on each face. For each face, one sensor is on the middle radius of the friction face of brake ring and the other two are on the middle radius ± 40 mm, circumferentially positioned with 120° of angle each other.

7.2.3.1 Test program 2A2 from UIC 541-3 with modified speed to 160 km/h.

Result temperatures from third prototype 2A2 test can be seen from picture below. As for 2A2 program, highest temperature during the test was 370°C.

Temperatures from 2A2 program were compliant to requirement of 375°C, as prescribed in report D1.1.

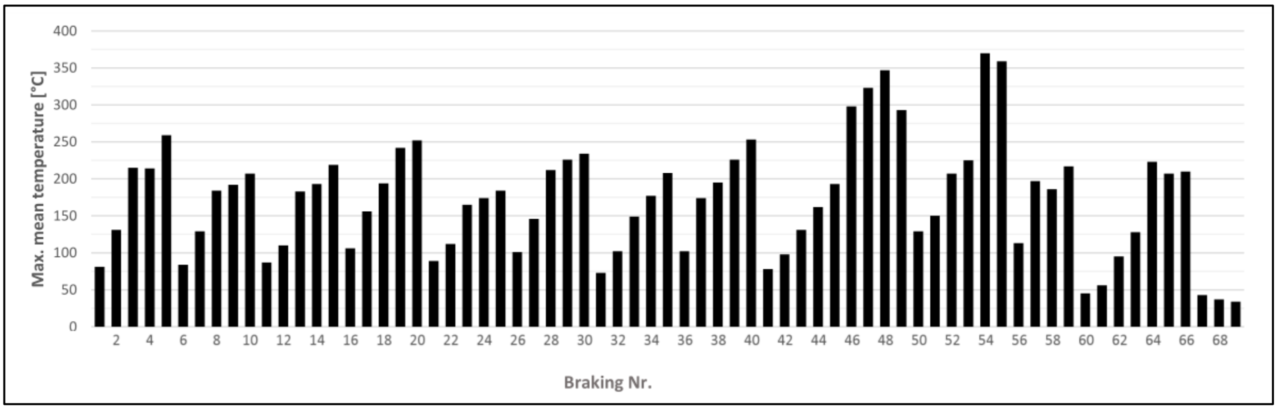


Figure 54: Temperatures of DRFB disc during 2A2 test program

7.2.3.2 Heat dissipation tests (Drag brake)

The purpose of the heat dissipation test was to qualify the thermal performance of the brake disc. So, the interest was to see the temperature and status of the discs after conducted tests at different power levels. The heat dissipation test of third prototype was done according requirements described in D1.1. The results are presented below.

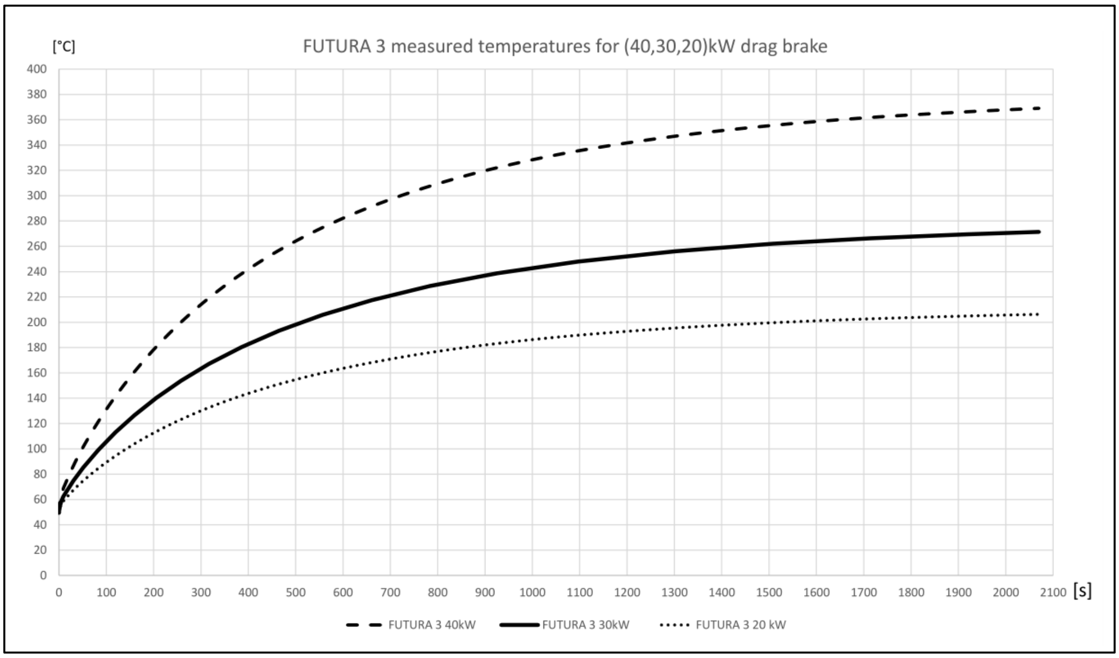


Figure 55: Temperatures of disc during heat dissipation test

Heat dissipation test temperatures at different power levels were from 206°C to 369°C, which was compliant to requirement of 450°C.

7.2.3.3 **DB – 175 Regulated braking (Thermal shock resistance)**

Program DB-175 is a program to verify thermal shock resistance against surface condition of the DRFB disc. This program consists of 175 braking from high velocity of 160 km/h to lower velocity of 80 km/h.

In this program, temperature is monitored and different conditions of the disc, like surface cracks and imbalance value were evaluated. Results of third prototype DB-175 test are presented below.

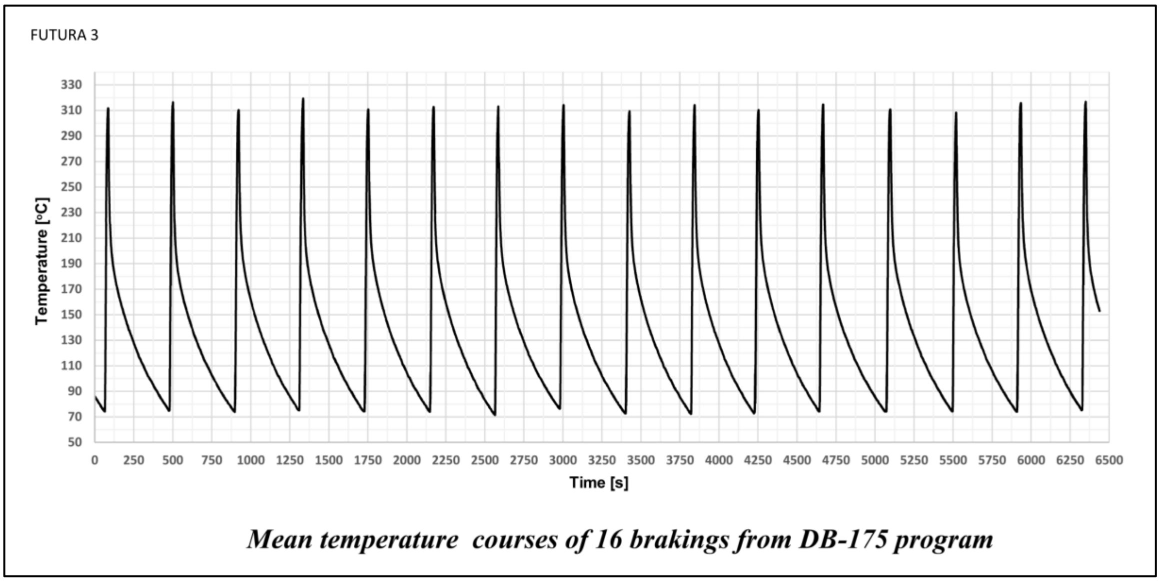


Figure 56: Temperatures of DRFB disc during DB-175 test

Result temperatures from DB-175 test can be seen from picture above. Highest temperature was 311°C, and on surface of the disc friction surface, there were no surface cracks.

Figure 57: 3rd prototype after DB-175 program

7.2.4 Vibrations measurements

In order to check vibrations caused by possible radial movement of the DRFB disc crown, there was a requirement for checking the imbalance value of the disc prior and after the heat dissipation test and 175 braking tests. Imbalance value was checked on special disc balancing machine.

Figure 58: 3rd prototype vibration measurement

According to requirements, the imbalance value after test cannot exceed the value measured before test by more than 20%. As a result, after tests, third prototype had allowable imbalance value, and it was compliant to requirements. Result is presented in the table below:

Table 35: Vibration measurements

	Measured value	Value before test	Allowable value
	[gm]	[gm]	20%
3rd prototype	14	14	0%

7.2.5 Coefficient of friction measurements between the DRFB disc and braking pads at different velocities and material degradation (corrosion, humidity, wet conditions)

Third prototype measurements of friction coefficient at different velocities, while simulating different weather condition, such as dry and wet condition at temperatures between 10°C and 30°C, as well as material degradation (corrosion, dust) were conducted within UIC program 2A2.

The coefficient of friction was measured throughout all program 2A2 for both dry and wet condition. The wet conditions were simulated with wetting device mounted on the test bench. The quantity of water during the wet braking was 21 litter per hour.

Braking at wet conditions created a layer of corrosion on the surface of the disc, and after drying, the disc collected dust from the braking pads degraded material. Then, the test continued in dry condition.

In this way, the coefficient of friction while simulating different weather conditions and degradation of material could be measured.

The coefficient of friction of third prototype, during the dry and wet braking for can be seen on picture below.

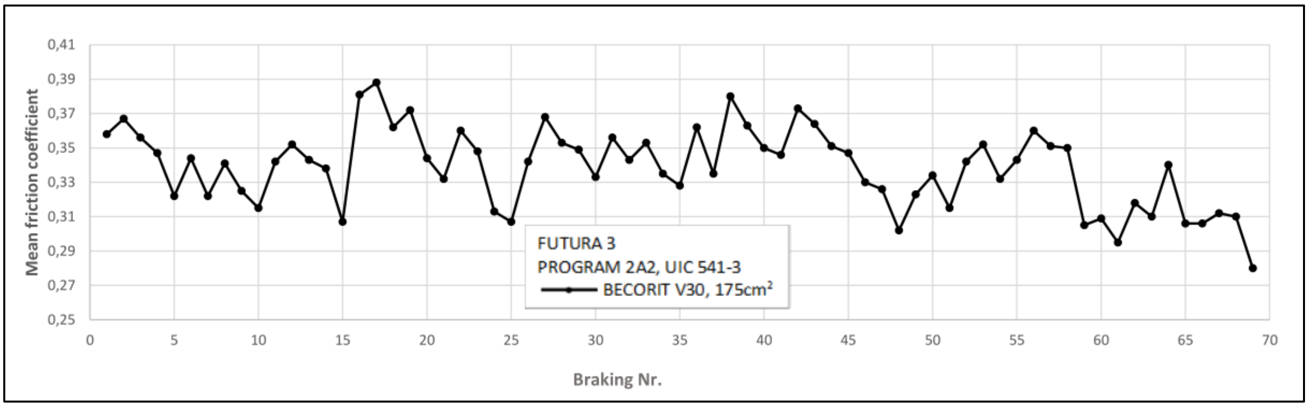


Figure 59: 3rd prototype friction coefficient (Program 2A2)

7.2.6 Ventilation test (power losses)

During this test, the aerodynamics of the DRFB disc can be seen, or, in another word, how much power is needed to keep the disc rotating at the constant speed. Ventilation properties of third prototype of DRFB disc were measured at 160 km/h and at 80 km/h.

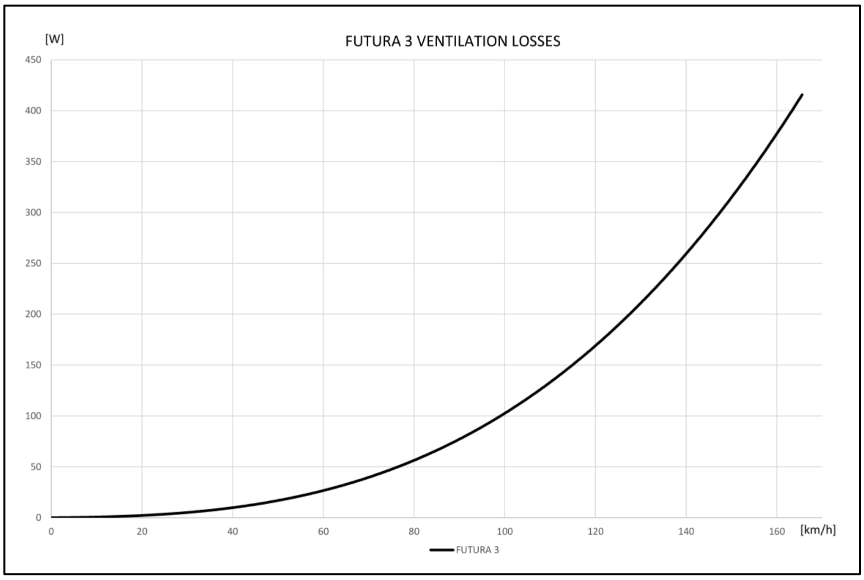


Figure 60: 3rd prototype ventilation losses

For third prototype maximum ventilation losses were 377 W at speed 160 km/h, which was not compliant to requirement of 350W.

7.2.7 Measurement of the wear of material (determining the mass and the volume of used material)

As prescribed in 2A2 program of UIC 541-3 standard, the wear of material (weighing) was done.

The weighing of pads was done after bedding-in, 41st, 45th and 57th braking. The total loss of mass, during the 2A2 program was 146 grams. As specific weight of the pad is around 2.18 g/cm3 and the spent energy was 253,97 MJ, the specific volume of wear after the test was 0,263 cm3/MJ. This value is compliant to prescribed requirement 0,28 cm^3.

Table 36: 3rd prototype pad wear

State after Nr. Of braking:	Mass [g]					Wear			
	1	2	3	4	Σ 1-4	[g]	$[cm^3]$ $(\rho = 2{,}18)$ $[g/cm^3]$	$[cm^3/MJ]$	Energy per interval [MJ]
R80	1077	1068	1068	1075	4288	53	24,40		
41	1063	1056	1064	1068	4251	37	16,81	0,10	165,83
45	1060	1051	1058	1053	4222	30	13,62	0,26	53,12
57	1055	1045	1047	1049	4196	26	11,97	0,34	35,02
					Σ=	146	66,79	0,263	253,97

8 4TH PROTOTYPE LABORATORY TESTS

8.1 4th prototype mechanical tests

8.1.1 Tensile test

Followed by third prototype tensile tests, three samples of fourth prototype were prepared for destructive tests. Results of these tests were compared with values stated on material certificates and material norms of production documentation for material EN-GJL-250 and C45E+QT.

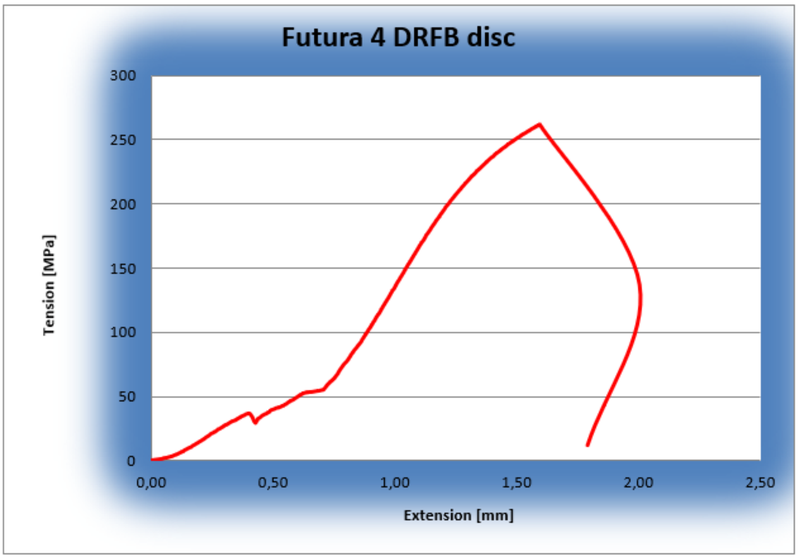


Figure 61: Graphic progress of 4th prototype DRFB disc crown tensile test

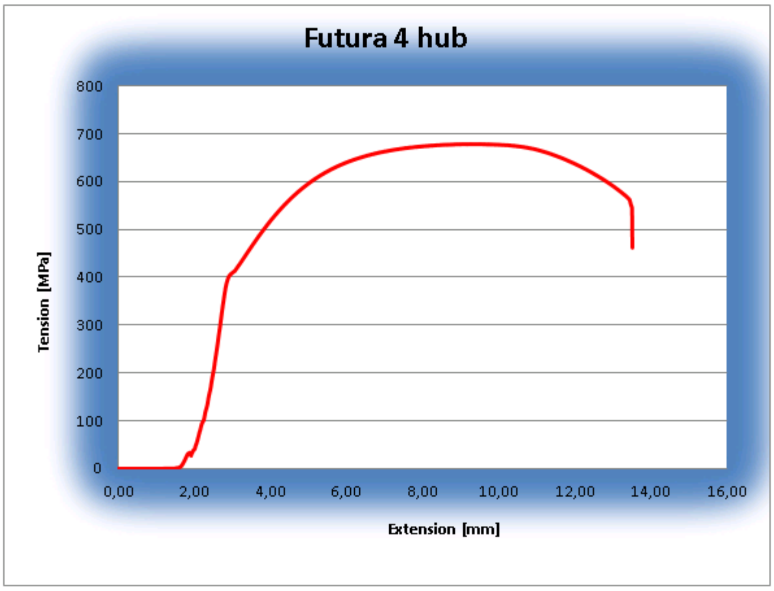


Figure 62: Graphic progress of 4th prototype DRFB disc hub tensile test

- 4th prototype results

All measured values of fourth prototype tests met given requirements. Results and requirements can be seen in the table below:

Table 37: 4th prototype tensile test results

No. of sample	Required values			Measured values (average)*			Result
	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	
DRFB disc crown	-	250-350	-	-	261	-	compliant
DRFB disc hub	min. 370	630-780	min. 17	402	679	19	compliant

8.1.2 Hardness test

Hardness tests of fourth prototype were performed according to EN ISO 6506-1 “Metallic materials - Brinell hardness test - Part 1: Test method”.

- 4th prototype results

All measured values of fourth prototype tests met given requirements. Results and requirements can be seen in the table below:

Table 38: 4th prototype hardness test results

No. of sample	Required values	Measured values (average)*	Result
	Hardness [HBW]	Hardness [HBW]	
DRFB disc crown	190-240	205	compliant
DRFB disc hub	187-235	210	compliant

8.1.3 Fatigue material test

Fatigue material tests were performed according to STN 42 0363 “Metal testing. Fatigue testing of metals. Methodology of testing”, and ISO 12107 “Metallic materials - Fatigue testing - Statistical planning and analysis of data”.

The objective of the test was to prove endurance strength at sample with non-modified (not grinded) surface of sample at level of stress δu= 114 MPa. Sample of material was loaded with cyclic loading force with sinusoidal course, and maximum amplitude which loads sample with stress above 114 MPa.

In case of crack stress is lowered, and the test are repeated. According to mentioned standards there can't occur a crack after completing 2 million of loading cycles with maximum stress higher than 114 MPa. Verification of surface crack is performed by non-destructive capillary control of surface defects on test sample. Positive test result will be confirmed between fatigue tests of two samples. All measured values of fourth prototype tests met given requirements. Results and requirements can be seen in the table below:

Table 39: 4^{th} prototype fatigue test results

No. of sample	Material	Required level of fatigue stress δu [MPa]	Level of stress without cracks 2 samples [MPa]
DRFB disc hub	C45E+QT	min. 114	218

8.1.4 Charpy test

Charpy impact tests of fourth prototype were performed according to EN ISO 148-1 "Metallic materials - Charpy pendulum impact test - Part 1: Test method".

Samples were prepared in accordance with standard EN ISO 148-1. Notch geometry "V" was used for preparation of samples. The V-notch had an included angle of 45°, depth of 2 mm, and a root radius of 0,25 mm.

- 4^{th} prototype results

All measured values of fourth prototype tests met given requirements, and are within required range. Results and requirements can be seen in the table below:

Table 40: 4th prototype Charpy test results

No. of sample	Required values	Measured values (average)*	Result
	K_v [J]	K_v [J]	
DRFB disc hub	min 32	45	compliant

8.1.5 Fracture toughness test

Fracture toughness test for fourth prototype were performed according to ISO 15653 “Metallic materials -- Method of test for the determination of quasistatic fracture toughness”. The objective of the test was to check resistance to fracture with test specimens already containing a crack.

- 4th prototype results

Results of fourth prototype fracture toughness tests of DRB disc and crown can be seen in the table below:

Table 41: 4th prototype hub fracture toughness test results

Load level	DRFB disc hub
	Force [kN]
F1	2,45
F2	5,92
F3	7,72

F1 – fracture toughness at generation of first crack

F2 – fracture toughness at generation of second crack

F3 – maximum fracture toughness

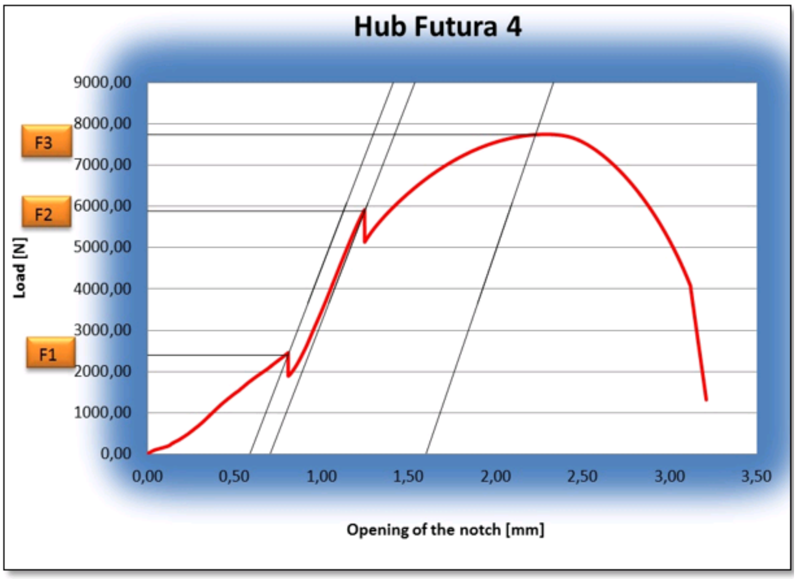


Figure 63: DRFB disc hub graphic fracture toughness test progress

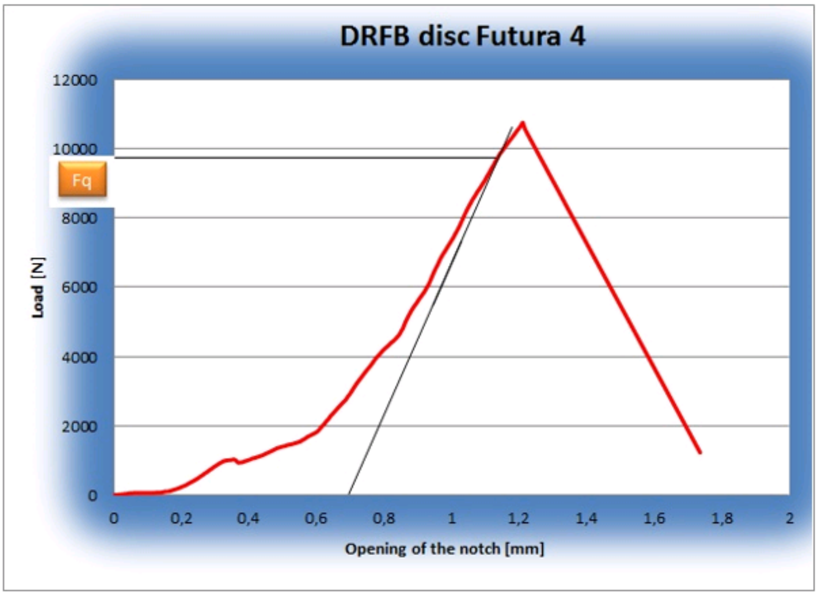


Figure 64: DRFB disc crown graphic fracture toughness progress

Table 42: 4th prototype crown fracture toughness test results

No. of sample	Required values according to EN 1561 – Annex A	Measured values
	K_{Ic} [MPa.m$^{1/2}$]	K_{Ic} [MPa.m$^{1/2}$]
1	17-20	20,3
2	17-20	20,3

8.2 4th prototype dynamical tests

Fourth prototype dynamical tests followed the same procedure as previous ones, and were performed on special dynamometric test bench for DRFB disc with maximum speed of 160 km/h, in order to check frictional, thermal, noise, and other properties of DRFB disc. The scope of tests was carefully chosen, and these tests were absolutely needed to confirm computer numerical calculations and to check performance of the disc.

Figure 65: 4th prototype DRFB disc

These tests were:

- Local noise measurements during braking
- Local noise measurements (unbraked, while rotating the DRFB disc at certain speeds)
- Temperature measurements by PT100 and PT1000 thermocouples at different positions on DRFB disc crown and hub during single and multiple braking
- Vibrations measurements (Imbalance measurements)
- Coefficient of friction measurements between the DRFB disc and braking pads at different velocities
- Coefficient of friction measurements between the DRFB disc and braking pads at material degradation (corrosion, dust, humidity, wet conditions)

- Ventilation tests (power losses)
- Measuring the wear and volume of material at single and multiple braking, determining the mass (grams) and the volume of used material (cm3/MJ)

8.2.1 Local noise measurements during braking

Same as for previous prototypes, noise level measurements during braking were conducted on fourth one during the UIC test program2A2. The microphone was positioned at 1m distance from the friction face of tested disc, and in the direction of the dynamometer axle and at the level of it.

As it can be seen from the table below, the highest level of noise of 90 dBA was during the 11th braking. The result was compliant to requirement of max. 90 dBA.

Table 43: 4th prototype noise level at braking

Braking nr.	Noise [dBA]	Initial speed [km/h]	Fb [kN]	Avg. friction coef.	Max. Temp.
11	90	120	40	0,348	211

8.2.2 Local noise measurements (unbraked disc)

The noise generation test was performed in order to ensure that a brake disc under rotation does not produce a noise over the acceptance limit. Noise generation test was made in accordance with deliverable D1.1, section 6.7. The noise (sound pressure level in dBA generated by the rotation of the disc was measured at the speed 160 km/h with a microphone. The microphone was positioned at 1 m distance from the friction face of the tested disc in the direction of the dynamometer axle and at the level of it.

The measurement of noise was conducted at maximum speed of 160 km/h until a steady state of speed was reached. Then the noise was recorded for two minutes.

As a result of noise measurement, fourth prototype had value of 54 dBA, which was compliant to requirement of 60 dBA prescribed in D1.1, section 6.7.1.

Table 44: 4th prototype noise test results

	Measured value	Requirement
	dBA	dBA
4th prototype	54	60

8.2.3 Temperature measurements at different positions on DRFB disc crown and hub during single and multiple braking

Temperature measurements were conducted for several tests for fourth DRFB discs prototype. These tests were performed according requirement described in D1.1. The scope of tests was:

- Test of frictional characteristic (Test program 2A2 from UIC 541-3 with modified speed to 160 km/h).
- Heat dissipation test (Drag brake)
- DB – 175 Regulated braking (Thermal shock resistance)

The DRFB brake discs were equipped with six temperature sensors positioned 1 mm below the friction surface, three on each face. For each face, one sensor is on the middle radius of the friction face of brake ring and the other two are on the middle radius ± 40 mm, circumferentially positioned with 120° of angle each other.

8.2.3.1 Test program 2A2 from UIC 541-3 with modified speed to 160 km/h.

Result temperatures from fourth prototype 2A2 test can be seen from picture below. As for 2A2 program, highest temperature during the test was 365°C.

Temperatures from 2A2 program were compliant to requirement of 375°C, as prescribed in report D1.1.

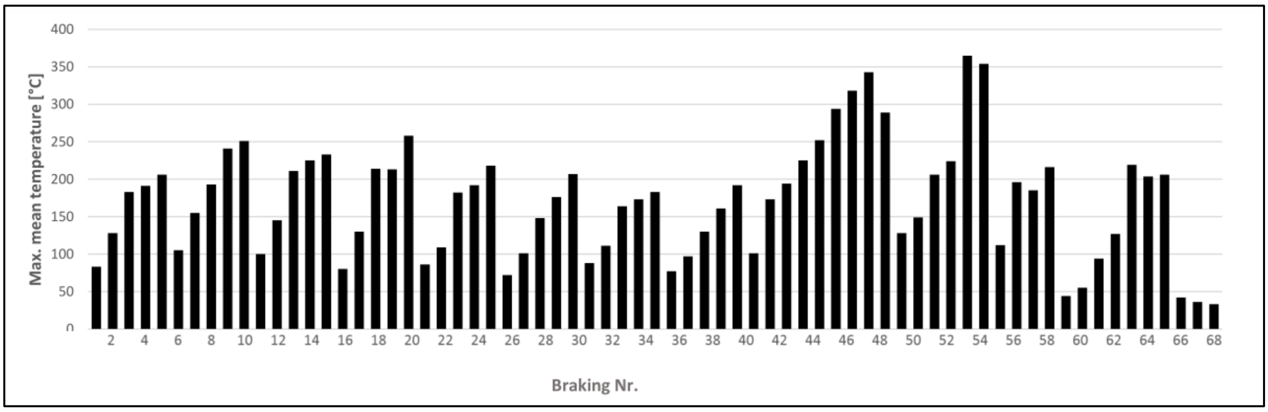


Figure 66: Temperatures of DRFB disc during 2A2 test program

8.2.3.2 Heat dissipation tests (Drag brake)

The purpose of the heat dissipation test was to qualify the thermal performance of the brake disc. So, the interest was to see the temperature and status of the discs after conducted tests at different power levels. The heat dissipation test of fourth prototype was done according requirements described in D1.1. The results are presented below.

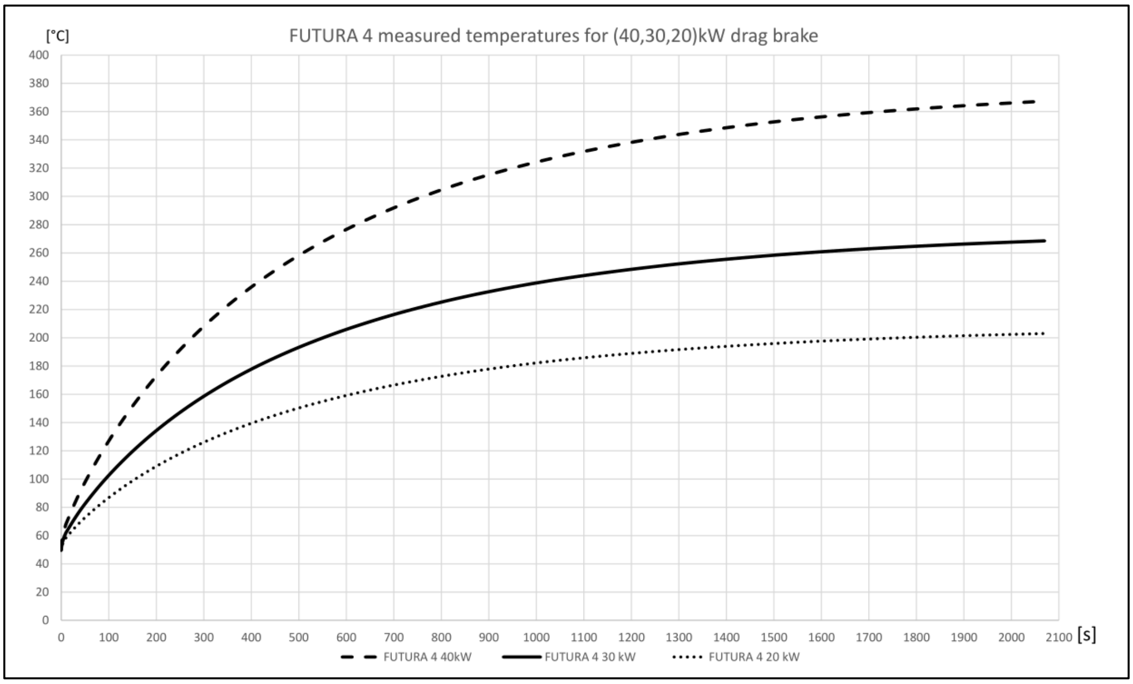


Figure 67: Temperatures of disc during heat dissipation test

Heat dissipation test temperatures of fourth prototype at different power levels were from 204°C to 369°C, which was compliant to requirement of 450°C.

8.2.3.3 DB – 175 Regulated braking (Thermal shock resistance)

Program DB-175 is a program to verify thermal shock resistance against surface condition of the DRFB disc. This program consists of 175 braking from high velocity of 160 km/h to lower velocity of 80 km/h.

In this program, temperature is monitored and different conditions of the disc, like surface cracks and imbalance value were evaluated. Results of fourth prototype DB-175 test are presented below.

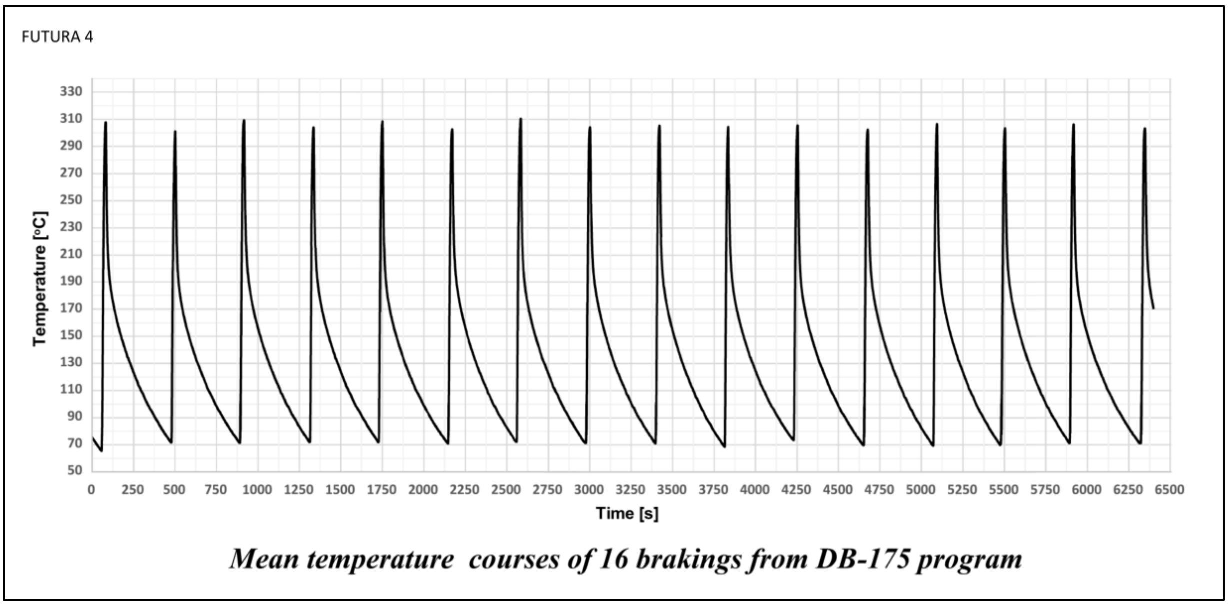


Figure 68: Temperatures of DRFB disc during DB-175 test

Result temperatures from DB-175 test can be seen from picture above. Highest temperature of fourth prototype was 306°C, and on surface of the disc friction surface there were no surface cracks present.

Figure 69: 4th prototype after DB-175 program

8.2.4 Vibrations measurements

In order to check vibrations caused by possible radial movement of the DRFB disc crown, there was a requirement for checking the imbalance value of the disc prior and after the heat dissipation test and 175 braking tests. Imbalance value was checked on special disc balancing machine.

Figure 70: 4th prototype vibration measurement

According to requirements, the imbalance value after test cannot exceed the value measured before test by more than 20%. As a result, after tests, fourth prototype had allowable imbalance value, and it was compliant to requirements. Result is presented in the table below:

Table 45: Vibration measurements

	Measured value	Value before test	Allowable value
	[gm]	[gm]	20%
4th prototype	13	13	0%

8.2.5 Coefficient of friction measurements between the DRFB disc and braking pads at different velocities and material degradation (corrosion, humidity, wet conditions)

Fourth prototype measurements of friction coefficient at different velocities, while simulating different weather condition, such as dry and wet condition at temperatures between 10°C and 30°C, as well as material degradation (corrosion, dust) were conducted within UIC program 2A2.

The coefficient of friction was measured throughout all program 2A2 for both dry and wet condition. The wet conditions were simulated with wetting device mounted on the test bench. The quantity of water during the wet braking was 21 litter per hour.

Braking at wet conditions created a layer of corrosion on the surface of the disc, and after drying, the disc collected dust from the braking pads degraded material. Then, the test continued in dry condition.

In this way, the coefficient of friction while simulating different weather conditions and degradation of material could be measured.

The coefficient of friction results of fourth prototype, during the dry and wet braking for can be seen on picture below.

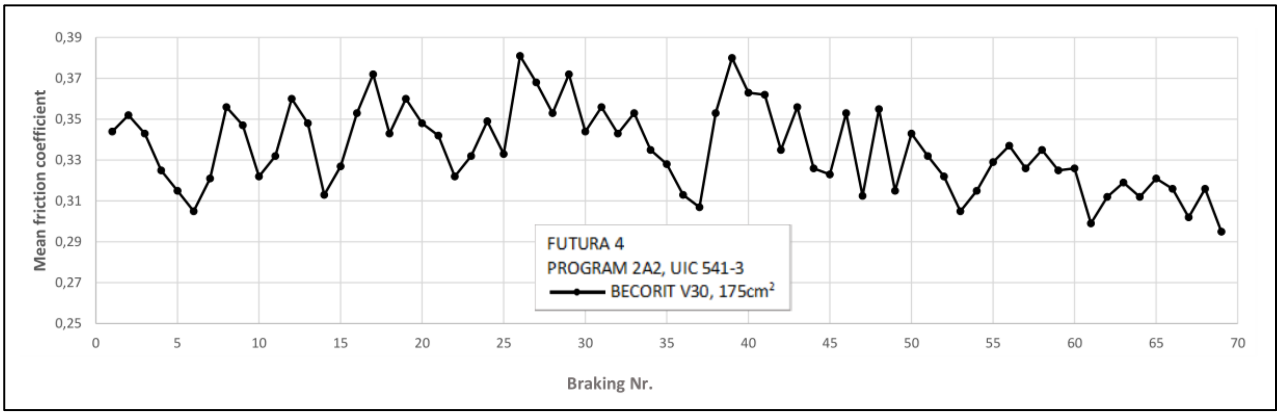


Figure 71: 4th prototype friction coefficient (Program 2A2)

8.2.6 Ventilation test (power losses)

During this test, the aerodynamics of the DRFB disc can be seen, or, in another word, how much power is needed to keep the disc rotating at the constant speed. Ventilation properties of fourth prototype of DRFB disc were measured at 160 km/h and at 80 km/h.

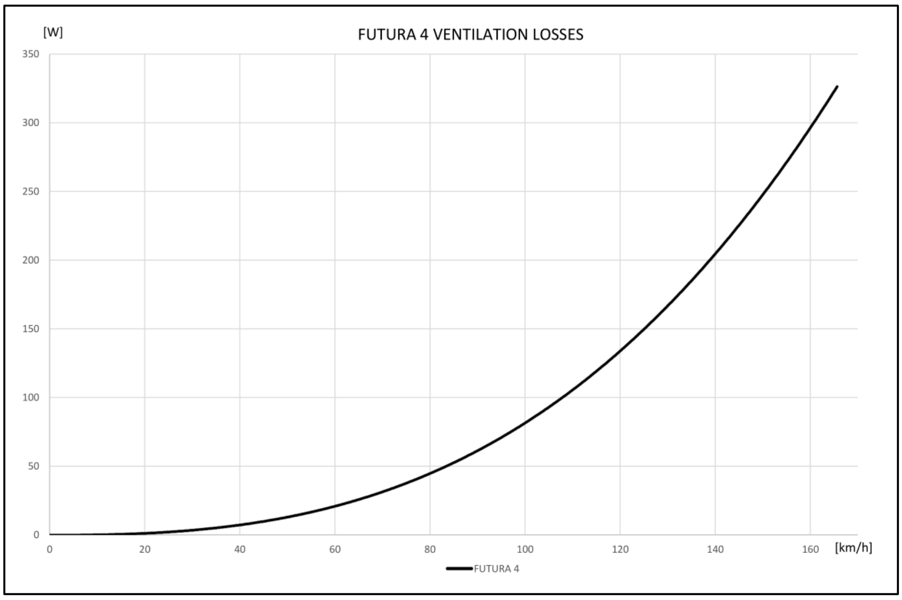


Figure 72: 4th prototype ventilation losses

For fourth prototype maximum ventilation losses were 297W at speed 160 km/h, which was compliant to requirement of 350W.

8.2.7 Measurement of the wear of material (determining the mass and the volume of used material)

As prescribed in 2A2 program of UIC 541-3 standard, the wear of material (weighing) of fourth prototype was done. The weighing of pads was done after bedding-in, 41st, 45th and 57th braking. The total loss of mass, during the 2A2 program was 144 grams. As specific weight of the pad is around 2.18 g/cm3 and the spent energy was 255,25 MJ, the specific volume of wear after the test was 0,259 cm3/MJ. This value is compliant to prescribed requirement 0,28 cm^3.

Table 46: 4th prototype pad wear

State after Nr. Of braking:	Mass [g]					Wear			
	1	2	3	4	Σ 1-4	[g]	$[cm^3]$ $(\rho = 2{,}18)$ $[g/cm^3]$	$[cm^3/MJ]$	Energy per interval [MJ]
R80	1062	1083	1072	1068	4285	48	22,02		
41	1052	1057	1062	1068	4239	46	21,10	0,13	166,74
45	1044	1048	1047	1054	4193	46	21,10	0,40	53,13
57	1043	1047	1046	1053	4189	4	1,83	0,05	35,38
					Σ=	144	66,06	0,259	255,25

9 5TH PROTOTYPE LABORATORY TESTS

9.1 5th prototype mechanical tests

9.1.1 Tensile test

Followed by fourth prototype tensile tests, three samples of fifth prototype were prepared for destructive tests. Results of these tests were compared with values stated on material certificates and material norms of production documentation for material EN-GJL-250 and C45E+QT.

As fifth prototype of DRFB disc used the same hub prototype as fourth one, there was no need to perform mechanical tests on the hub. Therefore, mechanical tests were conducted only on fifth DRFB disc crown prototype.

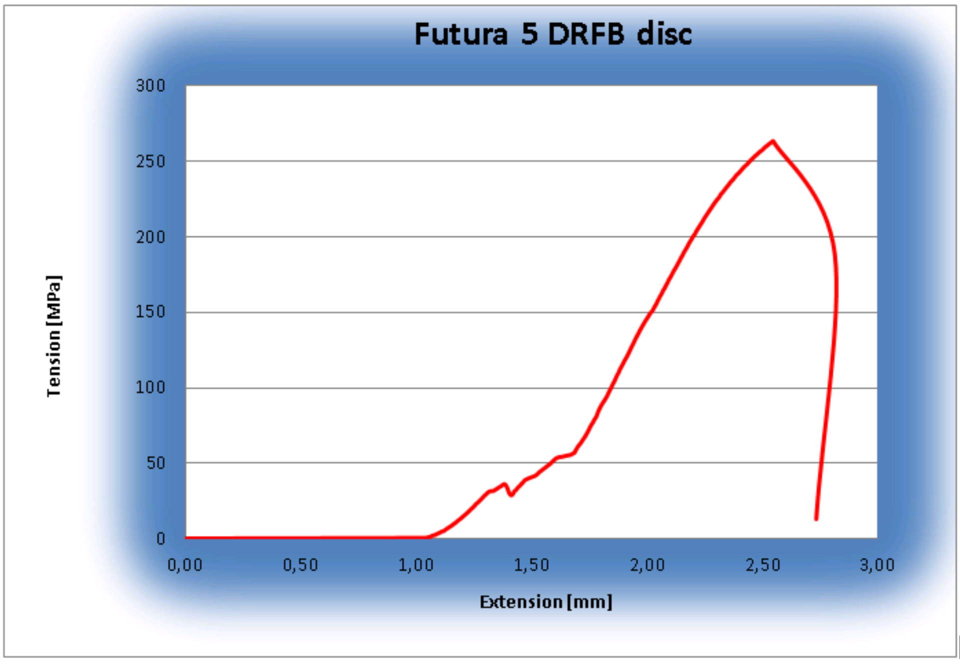


Figure 73: Graphic progress of 5th prototype DRFB disc crown tensile test

- 5th prototype results

All measured values of fifth prototype tests met given requirements. Results and requirements can be seen in the table below:

Table 47: 5th prototype tensile test results

No. of sample	Required values			Measured values (average)*			Result
	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	
DRFB disc crown	-	250-350	-	-	263	-	compliant

9.1.2 Hardness test

Hardness tests of fifth prototype were performed according to EN ISO 6506-1 “Metallic materials - Brinell hardness test - Part 1: Test method”.

- 5th prototype results

All measured values of fifth prototype tests met given requirements. Results and requirements can be seen in the table below:

Table 48: 5th prototype hardness test results

No. of sample	Required values	Measured values (average)*	Result
	Hardness [HBW]	Hardness [HBW]	
DRFB disc crown	190-240	212	compliant

9.1.3 Fatigue material test

As mentioned in previous chapter, fifth prototype of DRFB disc hub was used for both fourth and fifth prototypes of DRFB disc. So, there was no need to perform fatigue tests on the hub.

9.1.4 Charpy test

As same as for fatigue tests, Charpy impact tests of fifth prototype was not performed, due to fact that it is the same hub design as for fourth prototype.

9.1.5 Fracture toughness test

Fracture toughness test for fifth prototype of DRFB disc crown was performed according to ISO 15653 “Metallic materials -- Method of test for the determination of quasistatic fracture toughness". The objective of the test was to check resistance to fracture with test specimens already containing a crack.

- 5th prototype results

Results of fifth prototype fracture toughness tests of DRB disc and crown can be seen in the table below:

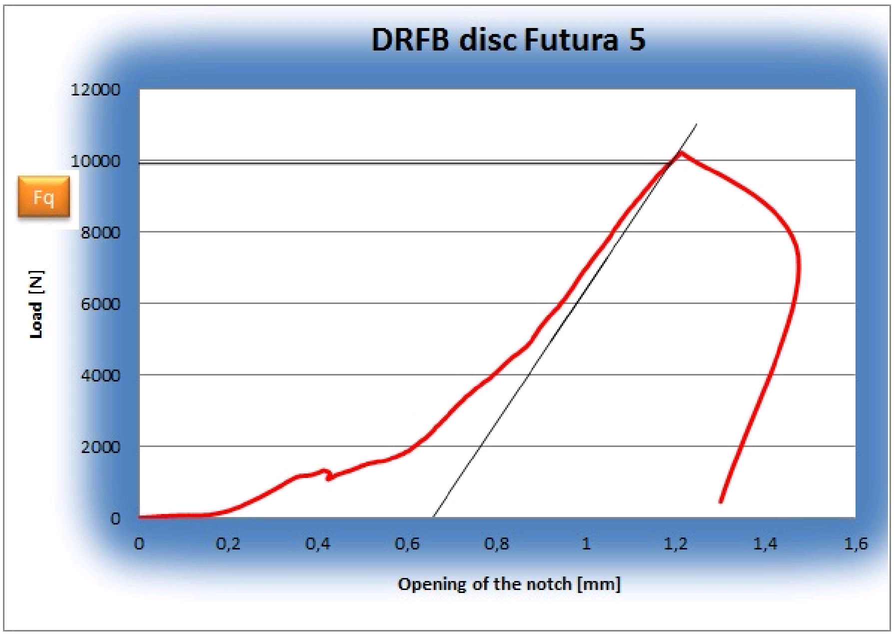


Figure 74: DRFB disc crown graphic fracture toughness progress

Table 49: 5th prototype crown fracture toughness test results

No. of sample	Required values according to EN 1561 – Annex A	Measured values
	K_{Ic} [MPa.m$^{1/2}$]	K_{Ic} [MPa.m$^{1/2}$]
1	17-20	20,9
2	17-20	20,85

9.2 5th prototype dynamical tests

Fifth prototype dynamical tests followed the same procedure as previous ones, and were performed on special dynamometric test bench for DRFB disc with maximum speed of 160 km/h, in order to check frictional, thermal, noise, and other properties of DRFB disc. The scope of tests was carefully chosen, and these tests were absolutely needed to confirm computer numerical calculations and to check performance of the disc.

Figure 75: 5th prototype DRFB disc

These tests were:

- Local noise measurements during braking
- Local noise measurements (unbraked, while rotating the DRFB disc at certain speeds)
- Temperature measurements by PT100 and PT1000 thermocouples at different positions on DRFB disc crown and hub during single and multiple braking
- Vibrations measurements (Imbalance measurements)
- Coefficient of friction measurements between the DRFB disc and braking pads at different velocities
- Coefficient of friction measurements between the DRFB disc and braking pads at material degradation (corrosion, dust, humidity, wet conditions)
- Ventilation tests (power losses)
- Measuring the wear and volume of material at single and multiple braking, determining the mass (grams) and the volume of used material (cm3/MJ)

9.2.1 Local noise measurements during braking

Same as for previous prototypes, noise level measurements during braking were conducted on fifth during the UIC test program2A2. The microphone was positioned at 1m distance from the friction face of tested disc, and in the direction of the dynamometer axle and at the level of it.

As it can be seen from the table below, the highest level of noise of 89 dBA was during the 32nd braking. The result was compliant to requirement of max. 90 dBA.

Table 50: 5th prototype noise level at braking

Braking nr.	Noise [dBA]	Initial speed [km/h]	Fb [kN]	Avg. friction coef.	Max. Temp.
32	89	140	14	0,348	236

9.2.2 Local noise measurements (unbraked disc)

The noise generation test was performed in order to ensure that a brake disc under rotation does not produce a noise over the acceptance limit. Noise generation test was made in accordance with deliverable D1.1, section 6.7. The noise (sound pressure level in dBA generated by the rotation of the disc was measured at the speed 160 km/h with a microphone. The microphone was positioned at 1 m distance from the friction face of the tested disc in the direction of the dynamometer axle and at the level of it.

The measurement of noise was conducted at maximum speed of 160 km/h until a steady state of speed was reached. Then the noise was recorded for two minutes.

As a result of noise measurement, fifth prototype had value of 56 dBA, which was compliant to requirement of 60 dBA prescribed in D1.1, section 6.7.1.

Table 51: 5th prototype noise test results

	Measured value	Requirement
	dBA	dBA
5th prototype	56	60

9.2.3 Temperature measurements at different positions on DRFB disc crown and hub during single and multiple braking

Temperature measurements were conducted for several tests for ffifth DRFB discs prototype. These tests were performed according requirement described in D1.1. The scope of tests was:

- Test of frictional characteristic (Test program 2A2 from UIC 541-3 with modified speed to 160 km/h).
- Heat dissipation test (Drag brake)
- DB – 175 Regulated braking (Thermal shock resistance)

The DRFB brake discs were equipped with six temperature sensors positioned 1 mm below the friction surface, three on each face. For each face, one sensor is on the middle radius of the friction face of brake ring and the other two are on the middle radius ± 40 mm, circumferentially positioned with 120° of angle each other.

9.2.3.1 **Test program 2A2 from UIC 541-3 with modified speed to 160 km/h.**

Result temperatures from fifth prototype 2A2 test can be seen from picture below. As for 2A2 program, highest temperature during the test was 412°C.

Temperatures from 2A2 program were not compliant to requirement of 375°C, as prescribed in report D1.1.

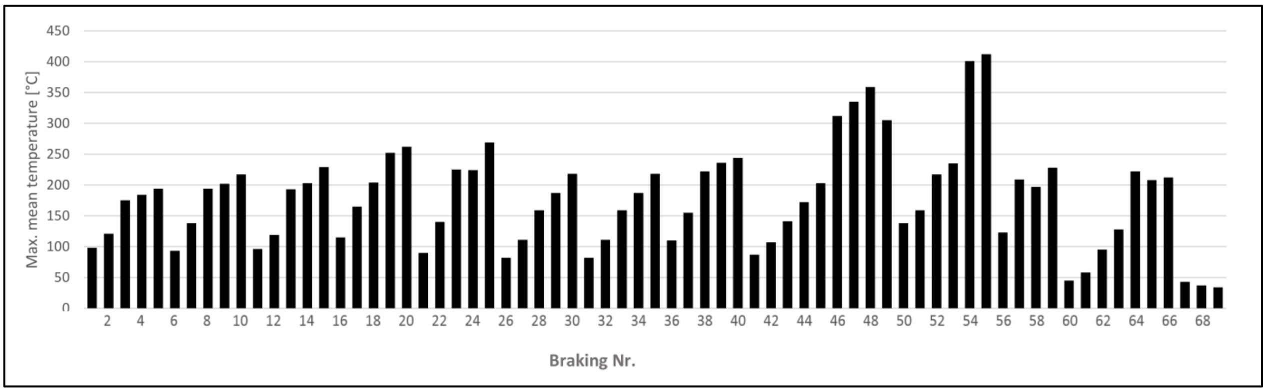


Figure 76: Temperatures of DRFB disc during 2A2 test program

9.2.3.2 **Heat dissipation tests (Drag brake)**

The purpose of the heat dissipation test was to qualify the thermal performance of the brake disc. So, the interest was to see the temperature and status of the discs after conducted tests at different power levels. The heat dissipation test of fourth prototype was done according requirements described in D1.1. The results are presented below.

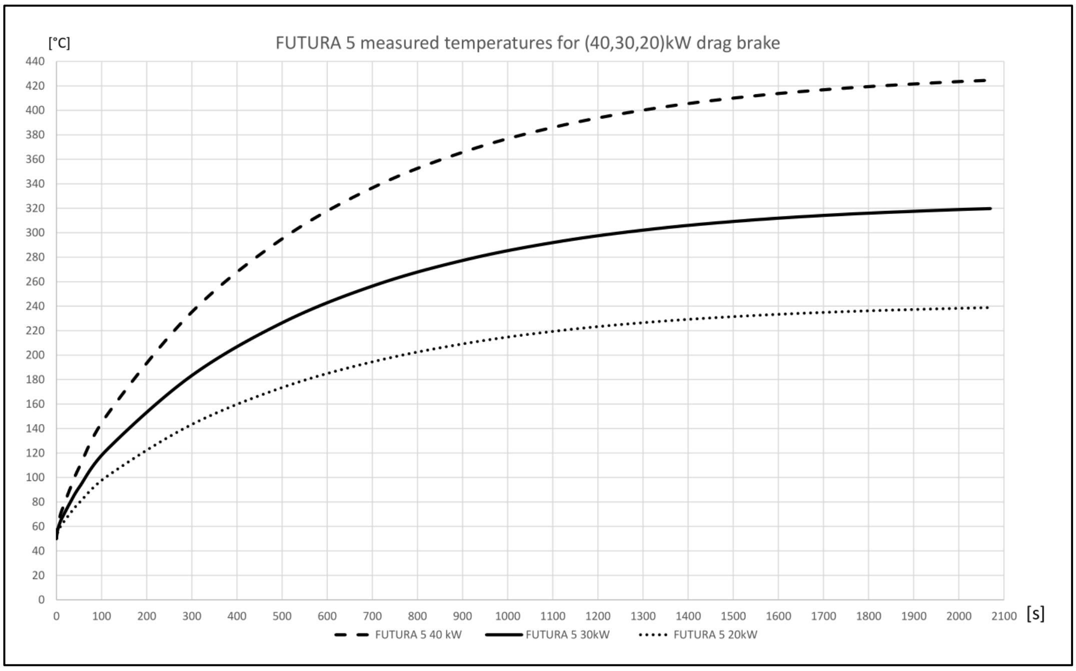


Figure 77: Temperatures of disc during heat dissipation test

Heat dissipation test temperatures of fifth prototype at different power levels were from 236°C to 322°C, which was compliant to requirement of 450°C.

9.2.3.3 DB – 175 Regulated braking (Thermal shock resistance)

Program DB-175 is a program to verify thermal shock resistance against surface condition of the DRFB disc. This program consists of 175 braking from high velocity of 160 km/h to lower velocity of 80 km/h.

In this program, temperature is monitored and different conditions of the disc, like surface cracks and imbalance value were evaluated. Results of fifth prototype DB-175 test are presented below.

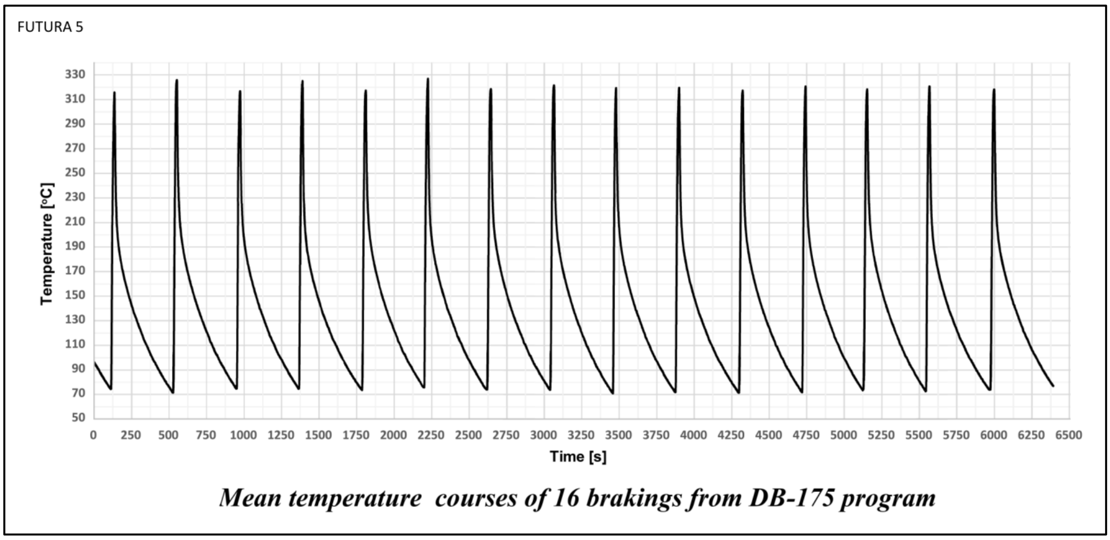


Figure 78: Temperatures of DRFB disc during DB-175 test

Result temperatures from DB-175 test can be seen from picture above. Highest temperature of fifth prototype was 320°C, and on surface of the disc friction surface there were no surface cracks present.

Figure 79: 5th prototype after DB-175 program

9.2.4 Vibrations measurements

In order to check vibrations caused by possible radial movement of the DRFB disc crown, there was a requirement for checking the imbalance value of the disc prior and after the heat dissipation test and 175 braking tests. Imbalance value was checked on special disc balancing machine.

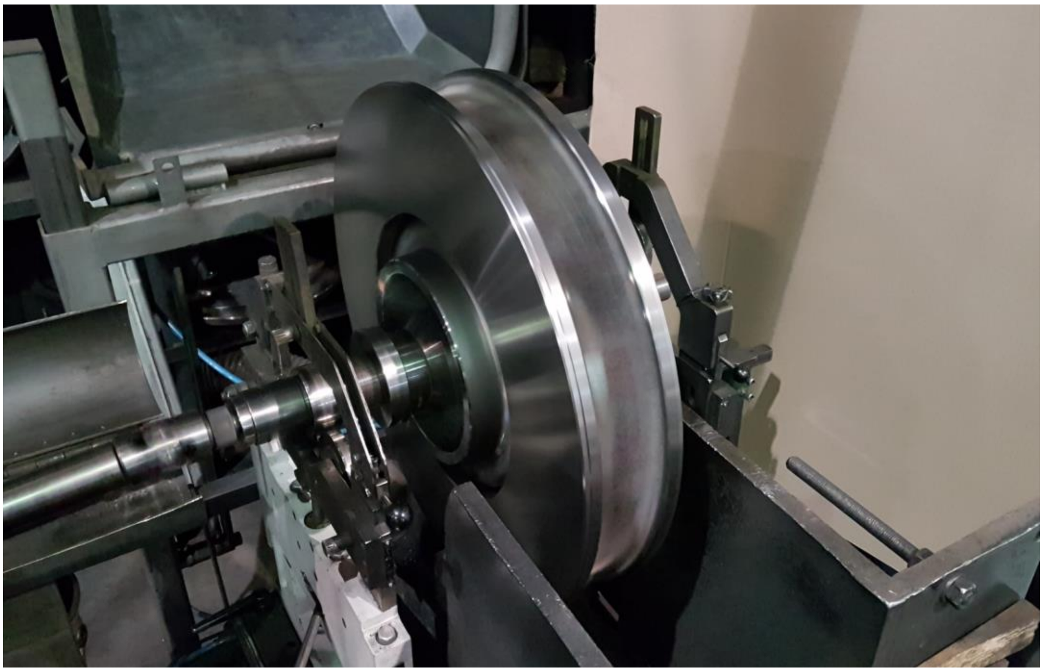


Figure 80: 5th prototype vibration measurement

According to requirements, the imbalance value after test cannot exceed the value measured before test by more than 20%. As a result, after tests, fifth prototype had allowable imbalance value, and it was compliant to requirements. Result is presented in the table below:

Table 52: Vibration measurements

	Measured value	Value before test	Allowable value
	[gm]	[gm]	20%
5th prototype	10	10	0%

9.2.5 Coefficient of friction measurements between the DRFB disc and braking pads at different velocities and material degradation (corrosion, humidity, wet conditions)

Fifth prototype measurements of friction coefficient at different velocities, while simulating different weather condition, such as dry and wet condition at temperatures between 10°C and 30°C, as well as material degradation (corrosion, dust) were conducted within UIC program 2A2.

The coefficient of friction was measured throughout all program 2A2 for both dry and wet condition. The wet conditions were simulated with wetting device mounted on the test bench. The quantity of water during the wet braking was 21 litter per hour.

Braking at wet conditions created a layer of corrosion on the surface of the disc, and after drying, the disc collected dust from the braking pads degraded material. Then, the test continued in dry condition.

In this way, the coefficient of friction while simulating different weather conditions and degradation of material could be measured.

The coefficient of friction results of fifth prototype, during the dry and wet braking for can be seen on picture below.

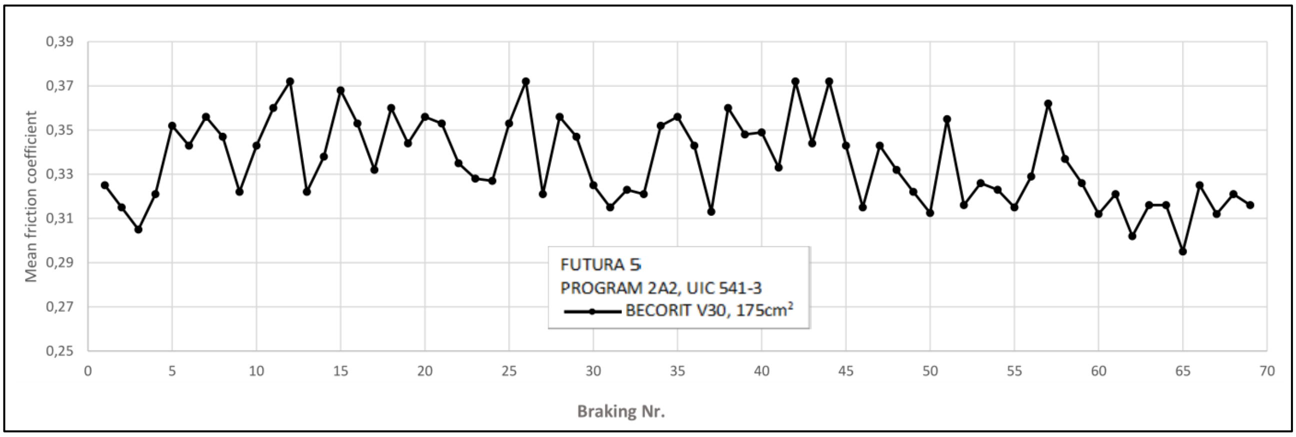


Figure 81: 5th prototype friction coefficient (Program 2A2)

9.2.6 Ventilation test (power losses)

During this test, the aerodynamics of the DRFB disc can be seen, or, in another word, how much power is needed to keep the disc rotating at the constant speed. Ventilation properties of fifth prototype of DRFB disc were measured at 160 km/h and at 80 km/h.

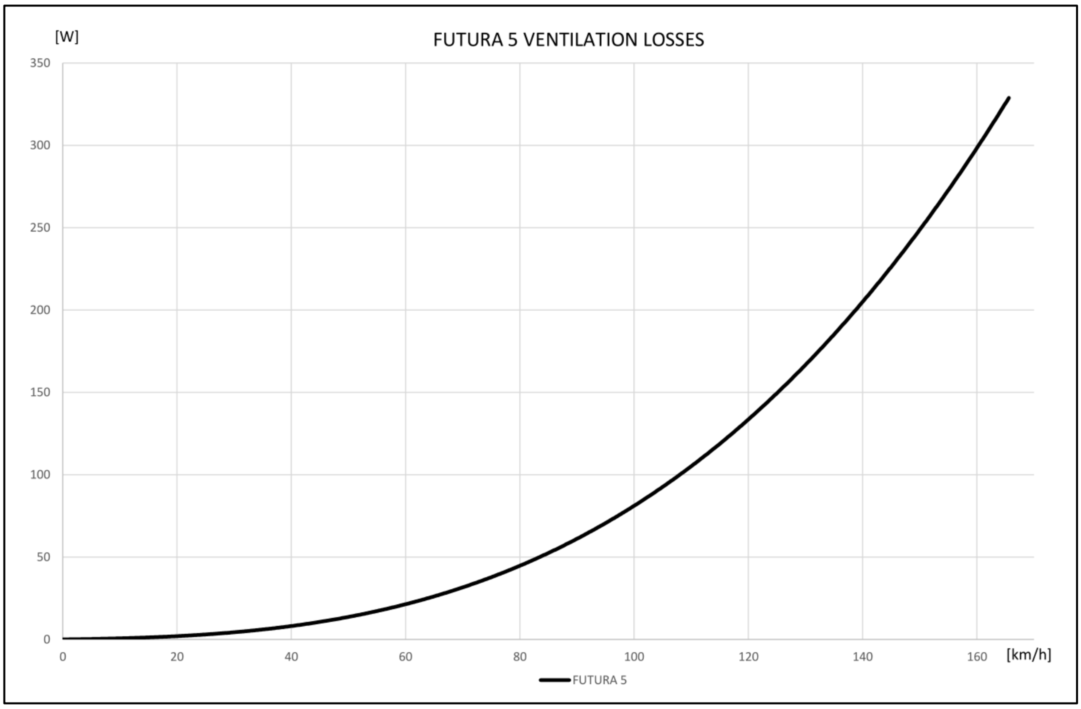


Figure 82: 5th prototype ventilation losses

For fifth prototype, maximum ventilation losses were 299W at speed 160 km/h, which was compliant to requirement of 350W.

9.2.7 Measurement of the wear of material (determining the mass and the volume of used material)

As prescribed in 2A2 program of UIC 541-3 standard, the wear of material (weighing) of fifth prototype was done. The weighing of pads was done after bedding-in, 41st, 45th and 57th braking. The total loss of mass, during the 2A2 program was 154 grams. As specific weight of the pad is around 2.18 g/cm3 and the spent energy was 253,73 MJ, the specific volume of wear after the test was 0,279 cm3/MJ. This value is compliant to prescribed requirement 0,28 cm^3.

Table 53: 5th prototype pad wear

State after Nr. Of braking:	**Mass [g]**					Wear			
	1	2	3	4	Σ 1-4	[g]	$[cm^3]$ $(\rho = 2{,}18)$ $[g/cm^3]$	$[cm^3/MJ]$	Energy per interval [MJ]
R80	1075	1081	1068	1069	4293	49	22,33		
41	1072	1056	1053	1065	4246	47	21,37	0,13	165,26
45	1045	1059	1054	1052	4210	36	16,57	0,31	53,13
57	1053	1042	1045	1047	4187	23	10,57	0,30	35,34
					Σ=	154	70,84	0,279	253,73

10 CONCLUSION ON LABORATORY TEST RESULTS

Mechanical and dynamical laboratory tests were needed to check frictional, thermal and mechanical characteristic of DRFB disc.

Laboratory tests were executed on five prototypes of DRFB disc crown and hub. As it can be seen from results of each prototype, mechanical characteristics of all of them were compliant to requirements. On the other hand, while performing dynamical tests, there were some deviations and non-compliance noticed.

During the UIC 541-3 track simulation program 2A2, first, second and fifth prototypes had higher temperatures than prescribed by standard. In despite of the temperature, all prototypes showed good frictional properties, with minor allowable surface cracks.

During the heat dissipation tests on different power levels of 20, 30, and 40kW, all prototypes showed good thermal properties. First, second and fifth prototypes had slightly higher temperatures than other ones, but still in prescribed limits. All prototypes were compliant to requirements.

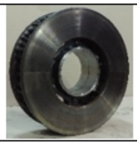
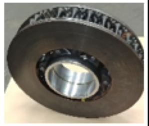
Noise levels at braking during the 2A2 program for first three prototypes were not compliant to requirements. On the other hand, fourth and fifth prototypes had slightly lower noise than prescribed, and results were acceptable.

Noise levels of unbraked (only rotating) DRFB disc were also measured at 160 km/h. Level of noise for all five prototypes was in between 52-57 dBA, which was compliant to requirement of 60 dBA.

Imbalance values, or main cause of vibrations were measured prior and after dynamical tests. As first three prototypes had the same execution of DRFB disc crown to hub connection (with bolts), there was a chance for vibrations to occur. According to requirement, the maximum imbalance value should not be more than 20%. Measurements of first three prototypes had value over the limit, and were not compliant to requirement.

On the other hand, third, fourth and fifth prototype had more firm and stable connection executed through special shape of connecting ears, and there was no chance for any vibrations to occur. As it can be seen from table below, results of imbalance values for third, fourth and fifth prototype were compliant to requirement, and there were no deviations in imbalance values prior and after dynamical tests.

Table 54: Overview and comparison of test results

Prototype		2A2 program temperatures [°C]	Heat dissipation temperatures at 20kW drag brake [°C]	Heat dissipation temperatures at 30kW drag brake [°C]	Heat dissipation temperatures at 40kW drag brake [°C]	DB-175 program [°C]	Ventilation losses [W] at 160 km/h	Noise level during 2A2 program braking [dBA]	Noise level Unbraked disc at 100 rad/s (160 km/h) [dBA]	Imbalance value before test [gm]	Imbalance value after test [gm]	Note
Initial		370	206	272	370	313	477	96	60	10	38	/
1st prototype		402	231	301	402	316	206	92	52	15	38	-8.4% mass
2nd prototype		404	230	299	401	315	378	93	56	7	36	-13.7% mass
3rd prototype		370	206	271	369	311	377	94	57	14	14	-20.7% mass
4th prototype		365	204	269	369	306	297	90	54	13	13	-22.7% mass
5th prototype		412	236	319	422	320	299	89	56	10	10	-34,5% mass

11 REFERENCES

[1] EN 14535-1: Railway applications – Brake discs for railway rolling stock– Part 1

[2] UIC 541-3: Brakes – Disc brakes and their application – General conditions for the approval of brake pads

[3] TSI 2008/861/EC: Technical specification for interoperability relating to the subsystem ‘rolling stock freight wagons’ of the rail system in the European Union

[4] KOVIS d.o.o.: Internal company documents