TRAIN-INDUCED AERODYNAMIC LOADS ACTING ON INSTALLATIONS OF GRANITZTAL TUNNEL

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ABSTRACT

In railway tunnels, highly dynamic pressure waves and flow-induced aerodynamic loads occur during train entry, passage, and exit. These loads act on all tunnel installations and must be considered in the design of the structural elements installed in tunnels. Due to the high number of daily train journeys and the associated high number of load cycles over the entire service life of the structural elements in tunnels, fatigue analyses, in addition to verifications of structural safety, are particularly important. During the planning phase, aerodynamic load assumptions were defined for the different installations in the Granitztal Tunnel, and these assumptions formed the basis for the design. The definition of these load assumptions was based on existing standards and regulations, as well as numerical simulation calculations and/or measurements of train-induced aerodynamic effects in comparable railway tunnels in Austria. During the commissioning runs of the Koralm railway line in 2025, the actual aerodynamic loads occurring during train journeys in the Granitztal Tunnel were measured and compared with the load assumptions defined for the design. This article describes and discusses the measurements carried out in the Granitztal Tunnel and the results obtained. It demonstrates that the aerodynamic load assumptions defined during the planning phase for the various tunnel installations are conservative, thus ensuring both the load-bearing capacity and fatigue resistance of the structures over their entire service life.

Keywords: aerodynamic loads, wake vortex, tunnel installations, dynamic amplification, fatigue.

1. INTRODUCTION

The dynamic loads resulting from train journeys in railway tunnels consist of pressure wave-induced and flow-induced aerodynamic loads (Figure 1) [1-3]. Pressure wave-induced loads (Figure 1a) arise immediately upon train entry and exit from the tunnel due to the sudden compression of air particles. The resulting pressure waves propagate at the speed of sound (343.2 m/s in dry air at 20°C) along the entire length of the tunnel. They alter the pressure field in the tunnel in a fraction of a second and, analogous to hydrostatic water pressure, act with the same magnitude in every direction on pressure-tight installations such as the tunnel emergency exit doors and ventilation flaps, which are tightly sealed towards the cross passages. For non-pressure-tight installations in tunnels such as signal signs, hectometer boards, suspension columns for the overhead conductor rail, ceiling power rail, and telecommunications cables, pressure compensation occurs due to the uniform impacts from all sides caused by pressure waves, resulting in no resulting stress or deformation reaction. Sudden pressure changes in the tunnel lead to shock loads on the tunnel installations, resulting in significantly greater deformation reactions compared to static loads. Therefore, a dynamic shock factor (magnification factor) of φ_{dyn} = 1.40 must be applied when designing tunnel installations [2].

Flow-induced aerodynamic loads (Figure 1b) arise when trains pass through the tunnel due to the air displacement and vortex shedding effects [4]. In the immediate vicinity of the train traveling through the tunnel, changes in the flow field occur starting from the train's front, with the simultaneous formation of highly turbulent vortex trails at the rear of the train and in the wake behind it. The tunnel installations located near the train – regardless of whether they are pressure-tight or not – are hence subjected to sudden dynamic stresses due to the flow-induced aerodynamic loads.

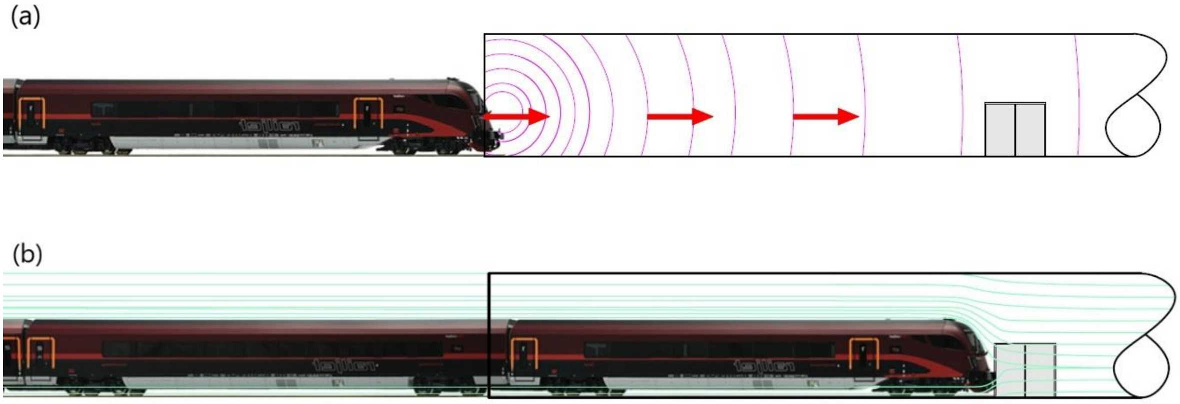


Figure 1: Pressure wave (a) and flow-induced (b) aerodynamic loads resulting from train journeys in railway tunnels

2. DESCRIPTION OF GRANITZ TUNNEL AND INSTALLED MEASUREMENT TECHNOLOGY

The Granitztal Tunnel is located at kilometer 75.812 (north portal, track 1) of the Austrian railway line 40101, west of St. Paul im Lavanttal. It is a double-tube, single-track railway tunnel with a total length of 6,106 m (Figure 2). The clear tunnel cross-section is 46 m² in the area of the ventilation center (constructed using the cut-and-cover method over a length of 606 m) and 41 m² in the remaining section (Langer Berg Tunnel and Deutsch Grutschen Tunnel). The tunnel was designed and built for a maximum train speed of 250 km/h.

To determine the actual aerodynamic loads occurring during train journeys, air pressure sensors were installed at five measurement cross-sections (MQi) in the southern tube of the tunnel (track 1, Graz direction) prior to the start of commissioning runs in February 2025 (Figure 2). Measurement cross-section MQ1 to MQ4 are located inside the tunnel tube, and for redundancy, two air pressure sensors were installed on the tunnel wall at each measurement point. Additionally, an autonomous train detection system was installed on the track at measurement point 1. This system allowed for the determination of the exact entry speeds of the trains and automated train type identification and classification, respectively. Measurement section 5 is located 25 m from the north portal of the Granitztal Tunnel, and in addition to the air pressure sensors, a sound level meter was also installed there to detect potential micropressure waves and sonic booms. This article focuses on investigating and assessing the actual magnitude of the train-induced aerodynamic loads within the tunnel, i.e., on analyzing the air pressure data recorded at measurement cross-sections 1 to 4.

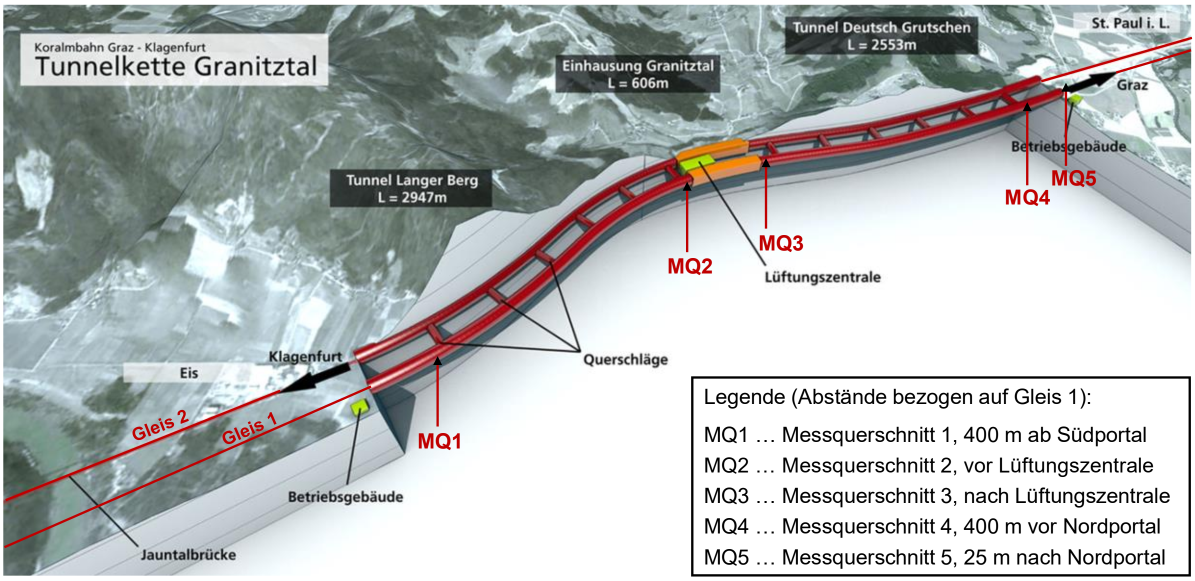


Figure 2: Twin-tube, single-track Granitztal Tunnel, measurement cross-sections MQ1 to MQ5

3. DEFINED DESIGN VALUES FOR AERODYNAMIC LOADING FOR TUNNEL INSTALLATIONS

The pressure wave and flow-induced aerodynamic loads resulting from train journeys in railway tunnels depend on the clear tunnel cross-section A_T, the train speed v_{ZUG}, the aerodynamic shape of the train, the train length, and the clearance dimension. The clearance dimension is defined as the ratio between the projected area of the train A_{ZUG} onto the vertical plane and the clear tunnel cross-sectional area A_T.

To determine the pressure wave-induced loads as a basis for the design of tunnel installations in new construction projects of ÖBB-Infrastruktur AG, extensive measurements of the actual pressure loads were carried out in 2014 in existing railway tunnels in Austria, such as the double-tube, single-track Wienerwald Tunnel. To generalize the measured pressure loads for different tunnel types (single-tube and double-tube), tunnel cross-sections, tunnel lengths, train types, and train speeds, as well as to investigate the relevant load case of "trains running in succession in long tunnels," numerical simulations of train operation in railway tunnels were performed using the software NUMSTA [5] in addition to the measurements. The computational models were then adapted to reality using the available measured values. To cover all possible (including future) operational trains, the TSI design train class 2 according to TSI LOC&PAS [6] was used in the simulation calculations. Finally, the characteristic aerodynamic pressure loads for different tunnel types, tunnel cross-sections, tunnel lengths, and train speeds were determined using the results of the extensive numerical simulation calculations [7]. The design values of characteristic aerodynamic loading for the structural safety and fatigue verification were defined differently for each of these scenarios. The increased dynamic deformation of the loaded structural element in railway tunnels resulting from the shock-like nature of the pressure loads, compared to a static load, was taken into account by adding the dynamic shock factor $\varphi_{dyn} = 1.40$ derived in [2]. Using formula (1), and after substituting the derived reference values for the minimum and maximum pressure (suction) for the reference tunnel cross-section $A_T = 40$ m², the maximum and minimum pressure wave-induced aerodynamic loads to be considered for the structural safety of tunnel installations can be determined as follow (Note: Equation (1) applies to train speeds 160 km/h $< V_{ZUG} \leq 250$ km/h):

$$p_{max,min} = p_{max,min,40m^2}\left(\frac{40}{A_T}\right)^{\frac{3}{2}} \cdot \varphi_{dyn} \qquad (1)$$

p_{max}	Maximum pressure wave-induced load (maximum pressure value) in Pascals
p_{min}	Minimum pressure wave-induced load (maximum suction value) in Pascals
$p_{max,40m^2}$	Reference value for maximum pressure at A_T = 40m² in Pascal ($p_{max,40m^2}$ = 7215 Pa)
$p_{min,40m^2}$	Reference value for minimum pressure at A_T = 40m² in Pascal ($p_{min,40m^2}$ = -8460 Pa)
A_T	clear tunnel cross-section in m²
φ_{dyn}	Dynamic shock factor (φ_{dyn} = 1.4)

For the Granitztal Tunnel, applying equation (1) and using the clear tunnel cross-section A_T = 41 m², the following values are obtained for the pressure wave-induced loads to be considered in the design of the tunnel installations for proof of load-bearing capacity: p_{max} = 9,700 Pa and p_{min} = 11,400 Pa. For the determination of the pressure wave-induced aerodynamic loads to be considered in the proof of fatigue resistance, see [7].

The determination of the flow-induced loads occurring during train journeys in railway tunnels, in addition to the pressure wave-induced aerodynamic loads, was based on DB Guideline 853 [8]. To account for the impact load effect, the dynamic shock factor φ_{dyn} = 1.40 was also added here. The maximum flow-induced pressure load can be calculated using equation (2):

$$q_{max} = 0{,}04726 \cdot \mathrm{u}^{*2} \cdot v_{ZUG}^2 \cdot \varphi_{dyn} \qquad (2)$$

u^*	Dimensionless air velocity as a function of the clear tunnel cross-section A_T according to DB guideline 853 [8]
v_{ZUG}	Train speed in km/h
φ_{dyn}	Dynamic shock factor (φ_{dyn} = 1.4)

For the Granitztal Tunnel, applying equation (2) and considering the clear tunnel cross-section A_T = 41 m², u^* = 1 according to DB guideline 853, and v_{ZUG} = 250 km/h, the following value is obtained for the maximum flow-induced pressure load to be used in the design of the tunnel installations: p_{max} = 4,135 Pa. This value was used in the design of all non-pressure-tight (flow-permeable) structural elements installed in the Granitztal Tunnel, such as signal signs, hectometer boards, suspension columns for the overhead conductor rail, ceiling power rail, and telecommunications cables. The pressure wave-induced loads do not need to be superimposed for these components, as pressure equalization occurs due to the pressure wave acting equally from all sides. Regarding fatigue design, it should be noted that the maximum pressure load must be determined according to equation (2) and the fatigue strength must be verified according to ÖNORM EN 1993-1-9 [9] with 5 million load cycles. Regarding the application limits of equation (2), it should be noted that it only calculates the flow-induced aerodynamic loads in the air gap between the moving train and the tunnel wall in the direction of travel. These load effects can therefore be used for the structural safety and fatigue design of all tunnel installations located in the air gap, which are subjected to airflow in or against the direction of travel of the train. However, practical experience has shown that the resulting aerodynamic load values for the design of tunnel installations subjected to airflow perpendicular to the direction of travel, such as telecommunications radiating cables, lead to a significant overestimation of the actual flow-induced loads occurring. In Austria, therefore, in 2021 a decision was made to carry out in-situ measurements on installations in existing railway tunnels to determine the actual flow-induced loads occurring perpendicular to the direction of travel of the train. The results of these measurements are documented and presented in [4].

4. MEASUREMENT OF ACTUAL AERODYNAMIC LOADS IN THE GRANITZTAL TUNNEL

To measure the actual aerodynamic loads occurring during train journeys in the Granitztal Tunnel, air pressure sensors were installed at five measurement cross-sections in the tunnel prior to the start of the Koralm railway line commissioning runs in February 2025 (see the description of the installed measurement equipment in Section 2 and the position of the five measurement cross-sections in Figure 2). The aim of the measurements was to verify the aerodynamic load assumptions for pressure wave and flow-induced loads, which were primarily based on theoretical considerations and used in the design of the tunnel structures for all tunnels on the Koralm railway line (see Section 3). Furthermore, a comparison between the theoretical and measured aerodynamic load values was to be carried out in order to assess the conservatism and safety level of the aerodynamic load assumptions. During the commissioning runs of the Koralm railway line in June 2025, the relevant journeys with regard to aerodynamic loads in the Granitztal Tunnel were carried out at speeds of up to 233 km/h. In the southern tube of the Granitztal Tunnel, which was equipped with air pressure sensors, the journeys listed in Table 1 were recorded, and the highest-pressure values were recorded for train journey no. 12 for the DANI train.

Table 1: Overview of measured train journeys, Granitztal Tunnel track 1 (south tube)

Train journey	**Type of train**	**Date, Time**	**Train Speed [km/h]**
1	Railjet set 35 with locomotive 1216 / control car at the front	10. Juni 2025, 08:54:15	181
2		10. Juni 2025, 10:33:45	201
3		10. Juni 2025, 15:06:55	231
4	Railjet set 35 with locomotive 1116 / control car at the front	11. Juni 2025, 08:52:02	181
5		11. Juni 2025, 10:45:21	201
6		11. Juni 2025, 12:34:38	231
7	Railjet set 35 with power car 6193 / control car at the front	12. Juni 2025, 08:55:15	182
8		12. Juni 2025, 10:44:30	202
9		12. Juni 2025, 12:30:47	230
10		12. Juni 2025, 14:31:07	232
11	Tfz 1116.235 with DANI day train set / 9-piece	13. August 2025, 08:34:00	201
12		13. August 2025, 11:30:21	233
13		13. August 2025, 14:16:42	232
14	Tfz 1216.235 with CD-ComfortJet (9-piece set / 12-piece set)	21. August 2025, 09:06:52	199
15		21. August 2025, 11:39:08	230
16		21. August 2025, 14:07:21	233

Figure 3 shows the maximum and minimum pressure loads measured at the measurement cross-section MQ1 as a function of train speed. It can be seen that at MQ1, at the highest speed of 233 km/h (test run no. 12), a maximum value of approximately 3,600 Pa and a minimum value of approximately -1,800 Pa were measured. The speed dependence of the pressure loads is clearly visible in the diagram.

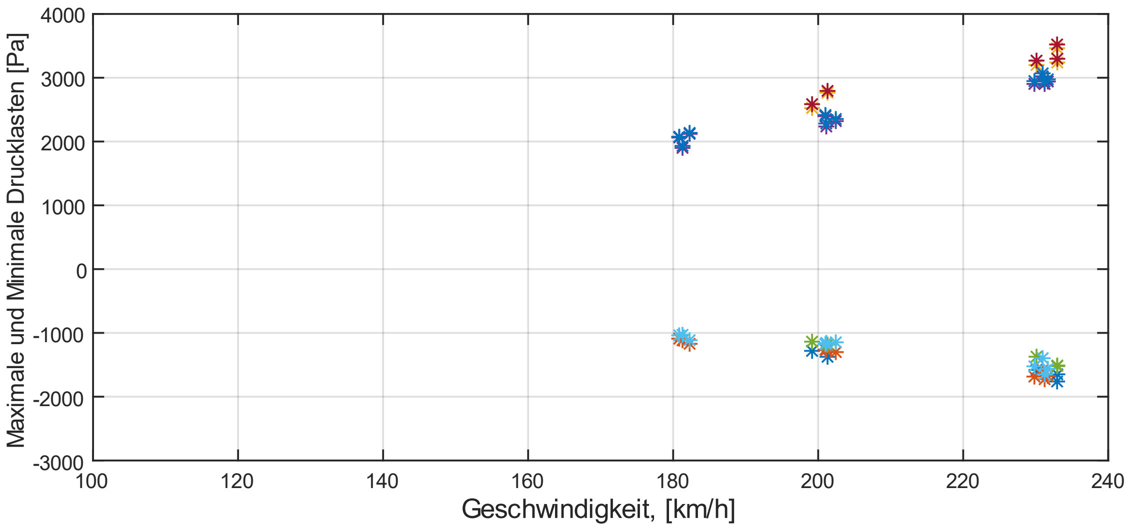
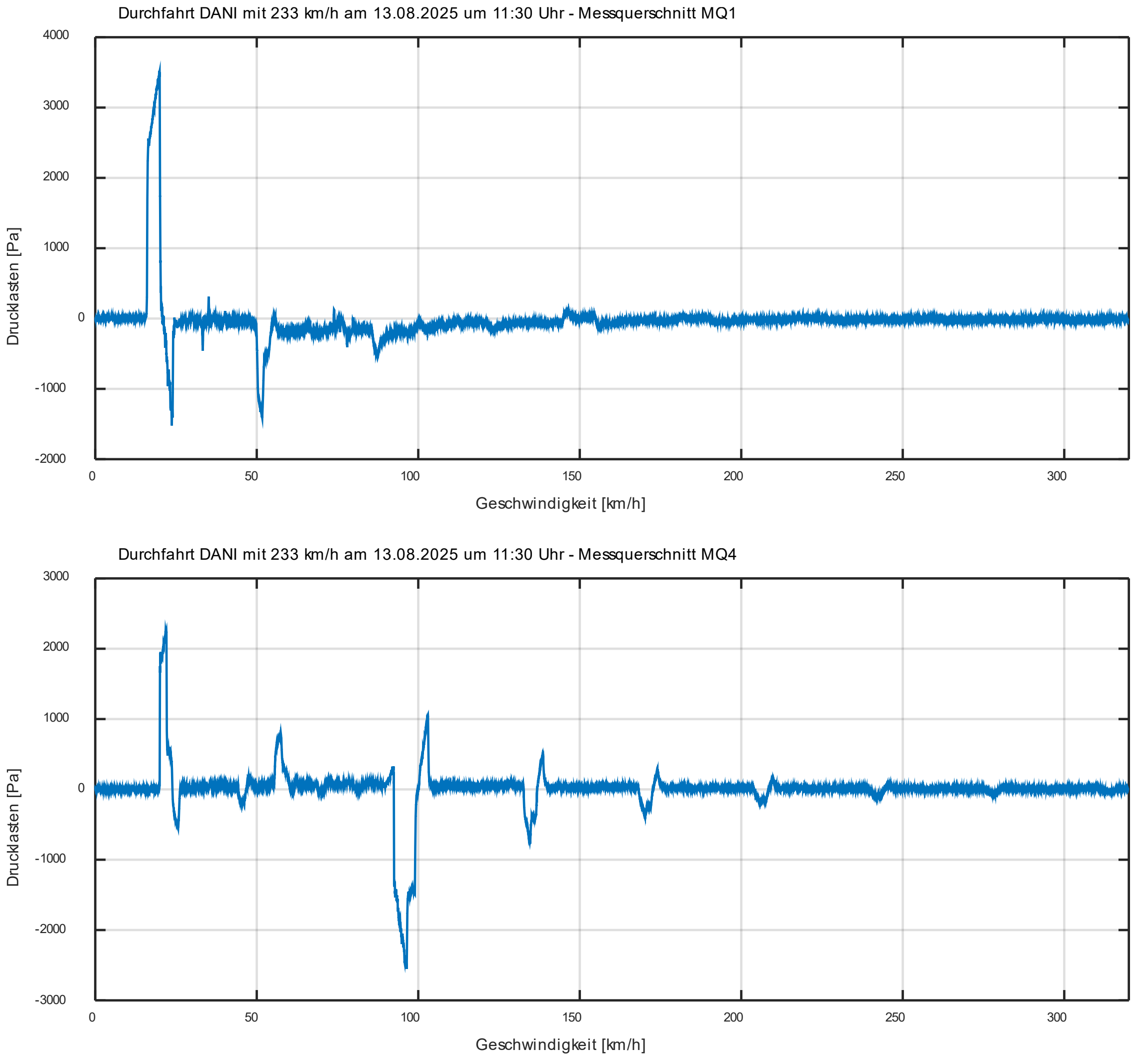


Figure 3: Measured maximum and minimum pressure loads as a function of the travel speed of the trains in the tunnel at measurement cross-section MQ1


Durchfahrt DANI mit 233 km/h am 13.08.2025 um 11:30 Uhr - Messquerschnitt MQ1

Durchfahrt DANI mit 233 km/h am 13.08.2025 um 11:30 Uhr - Messquerschnitt MQ4

Figure 4: Pressure loads measured during passage of the DANI day train set at 233 km/h at measurement cross-section MQ1 (near the entrance portal) and MQ4 (near the exit portal).

Figure 4 shows the measured pressure load time histories for the train passage at 11:30:21 on August 13, 2025, at 233 km/h (DANI daytime train), which is decisive with regard to the highest-pressure values. The time histories displayed are taken at MQ1 (near the entrance portal) and MQ4 (near the exit portal). It is clearly evident that multiple reflections of the pressure waves occur and that the highest maximum values ($p_{max} \approx 3{,}600$ Pa) are measured at measurement cross-section MQ1 (close to entry portal), while the highest minimum values ($p_{min} \approx -2{,}700$ Pa) are measured at measurement cross-section MQ4 close to exit portal). The highest maximum pressure loads always occur close to the tunnel entry portal, while the highest minimum pressure loads always occur near the exit portal and depend on the tunnel length. For the comparison of the theoretical aerodynamic loads to the measurement results to be carried out in Section 5, the measured pressure loads must be multiplied by the dynamic shock factor $\varphi_{dyn} = 1.40$ due to their impact-like nature, resulting in the following comparative pressure loads: $p_{max,M,\varphi}$ = approx. 5,040 Pa and $p_{min,M,\varphi}$ = approx. -3,780 Pa.

5. SUMMARY AND CONCLUSION

For the Granitztal Tunnel and also for all other tunnels on the Koralm railway line, pressure wave-induced aerodynamic loads of $p_{max} = 9{,}700$ Pa and $p_{min} = -11{,}400$ Pa were specified during the planning phase for the design regarding proof of load bearing capacity of all pressure-tight tunnel installations, such as emergency exit doors and ventilation flaps to cross passages (see Section 3). In contrast, during the train runs carried out in 2025 among others with DANI daytime train set at the maximum speed of 233 km/h, taking into account the dynamic shock factor $\varphi_{dyn} = 1.40$, the measured pressure loads were determined to be $p_{max,M,\varphi}$ = approx. 5,040 Pa and $p_{min,M,\varphi}$ = approx. -3,780 Pa. Therefore, the measured train runs result in a utilization of 0.52 for $p_{max,M,\varphi} / p_{max}$ and 0.33 for $p_{max,M,\varphi} / p_{min}$. The load-bearing capacity of the installed pressure-tight tunnel installations in the Granitztal Tunnel is therefore fulfilled with a high degree of safety, and this can also be assumed for fatigue safety.

6. REFERENCES

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