Reserves in load capacity assessment of existing bridges

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Abstract. High percentage of all railway bridges in the Czech Republic is made of structural steel. Majority of these bridges is designed according to historical codes and according to the deterioration, they have to be assessed if they satisfy the needs of modern railway traffic. The load capacity assessment of existing bridges according to Eurocodes is however often too conservative and especially, braking and acceleration forces cause huge problems to structural elements of the bridge superstructure. The aim of this paper is to review the different approaches for the determination of braking and acceleration forces. Both, current and historical theoretical models and in-situ measurements are considered. The research of several local European state norms superior to Eurocode for assessment of existing railway bridges shows the big diversity of used local approaches and the conservativeness of Eurocode. This paper should also work as an overview for designers dealing with load capacity assessment, revealing the reserves for existing bridges. Based on these different approaches, theoretical models and data obtained from the measurements, the method for determination of braking and acceleration forces on the basis of real traffic data should be proposed.

1. Introduction

The Czech Republic has one of the most dense and oldest railway networks in the world. Its history reaches back to the beginning of the 19th century. Due to the several historical and political reasons its development stagnated in the second half of the 20th century. Despite the tradition of railway transportation and the size of the railway network, it quickly became outdated in comparison to western neighboring countries. During the early stages of the railway construction, the steel bridges were widely used to span long and medium distances. Apart from their practical purpose, these bridges have often great architectural and historical value. Nowadays, the needs of transportation rapidly grow and the modern codes reflect these needs by introducing new traffic models and approaches for calculation of load capacity of existing bridges. In the Czech Republic, the Eurocodes are used for the design and assessment of bridge structures. Eurocodes are often too conservative for the historical steel bridges, which are in many cases part of the local railway tracks with lower transportation importance.

One of the load actions, which often limit old bridges designed according to historical norms, are braking and acceleration forces. Although these forces do not usually have impact on the overall load capacity of the main load-bearing superstructure, the cross-beams and horizontal bracing members do not usually satisfy the structural checks.

The aim of this paper is to review the methods for braking and acceleration forces determination. Even though majority of European countries use Eurocodes for design and assessment of new bridges, many national authorities for railway transportation have their own approaches for load capacity calculation of existing bridges. These methods are either based on national historical norms or at least adjust the Eurocode models.

2. The development of braking and acceleration forces

In the following paragraphs is the summary of historical norms used in the Czechoslovakia and the Czech Republic. This chapter outlines the models used for calculation of acceleration and braking forces.

Table 1. The list of historical norms used in the Czechoslovakia and the Czech Republic until Eurocode introduction. One example of load model is shown for all codes.

Designation	Original name	English translation	Period	Load Model
-	Nový mostní řád	New Bridge Regulations	1904-1923	2x119t+3.7t/m
-	Československý mostní řád	Czechoslovak Bridge Regulations	1923-1937	2x150t+8.0t/m
ČSN 1230	Jednotný mostní řád	Unified Bridge Regulations	1937-1941	2x150t+8.0t/m
-	Výnos ministerstva dopravy	Ministry of Transport Proceeds	1941-1950	2x175t+8.0t/m
-	Smernice pro navrhování mostů	Bridge Design Guidelines	1950-1953	2x175t+8.0t/m
ČSN 73 6202	Zatížení a statický výpočet mostů	Loads and Structural Analysis of Bridges	1953-1968	2x192t+7.6t/m
ČSN 73 6203	Zatížení mostů	Load Actions on Bridges	1968-1987	2x192t+7.6t/m
ČSN 73 6203	Zatížení mostů	Load Actions on Bridges	1987-2004	UIC 71

Until the ČSN 73 6203 – Zatížení mostů (Load actions on bridges) which was used between year 1987 and 2004, all previous norms had assumed the braking forces as 10% of the overall weight of the whole train. This was limited to bridges in open track and stations with maximum horizontal allignment of 10‰. The dynamic coefficient was introduced and used since the Jednotný mostní řád (Unified Bridge Regulations) 1937-1941.

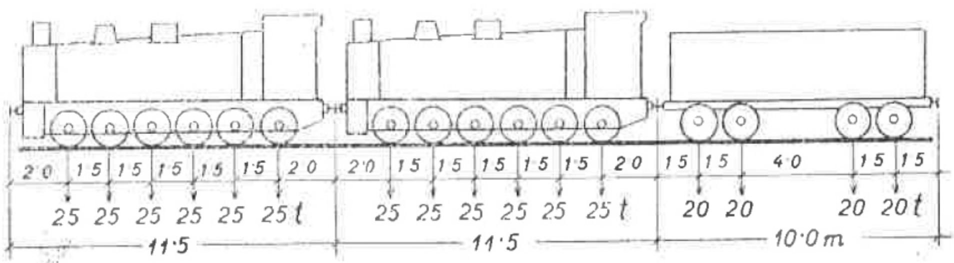

Figure 1. The load model from the Czechoslovak Bridge Regulations.

In the ČSN 73 6203 – Zatížení mostů (Load actions on bridges) 1987-2004 new concept of braking and acceleration forces calculation was implemented. Acceleration forces were introduced acting against the train direction of travel, where braking forces act in the direction of travel. The friction coefficient is used for calculation of both, braking and acceleration forces. The coefficient depends on the type of acting force, the used connections of the rail and the presence of rail expansion joints, stiffness of bearings and the loaded length of the bridge. The friction coefficient is based on the theoretical model ČSD – Frýba theory [1] and the results of vast measurements made under the UIC ORE D 101 research in 1967 focused on the braking and acceleration forces.

3. The current standards and national codes

3.1. EN 1991-2: Eurocode 1: Actions on structures – Part 2: Traffic loads on bridges

This norm should be used in all countries in European Union for the determination of traffic load actions on bridges. Acceleration and braking forces in this code match those in *UIC 774-3 R – Track/bridge interaction, recommendations for calculations*.

The acceleration and braking forces are calculated from the loaded length of the bridge for load models LM71 and heavy train load models SW according to following equations.

$$Q_{lak} = 33[kN/m]L_{a,b}[m] \leq 1000[kN] \quad (1)$$

$$Q_{lbk} = 20\ [kN/m]L_{a,b}[m] \leq 6000[kN] \quad (2)$$

The characteristic values are not multiplied by dynamic coefficient or reduction factor. The values are multiplied by load classification factor. In the case of specified traffic on the track, the acceleration and braking forces can be taken as 25% of the acting axel load. For bridges, shorter than 40 m, the forces in bearings may be reduced depending on the type of rail connections and expansion joints.

3.2. RIL 804 – Railway bridges and other engineering structures – construction and maintenance

The value of acceleration and braking forces in the German code is estimated according to the EN 1991-2. However, the reduction factor for of the bearing load depending on the rail connections and expansion joints is defined up to 300 m. The reduction factor varies between 0.5 and 0.9.

The *RIL 805 – Safety of existing railway bridges* defines the lower upper limit for acceleration forces on the non-electrified sections of the track.

3.3. SIA 269 – Maintenance of structures – load actions

This swiss norm adjusts the *SIA 261 – Load actions on structures* for existing bridges. The value of acceleration forces is not modified. However, the braking forces and their upper limits differ for various categories of tracks based on the traffic density, and they are up to 10% percent lower, than Eurocode.

3.4. TDOK 2013:0267 – Calculation of load capacity of existing bridges

The acceleration and braking forces are calculated according to this Swedish norm as 1/7 of the vertical load. The forces are limited to 4000 kN for the load models TLM 1 and TLM 2 (axle load of 300 kN) and to 6000 kN for the load model TLM 3 (axle load of 350 kN).

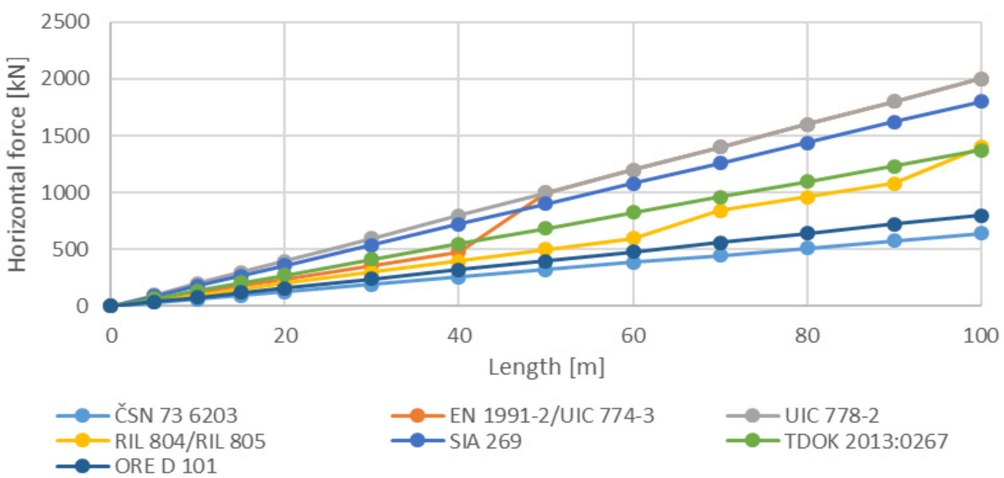

Figure 2. Braking forces according to different current and historical codes.

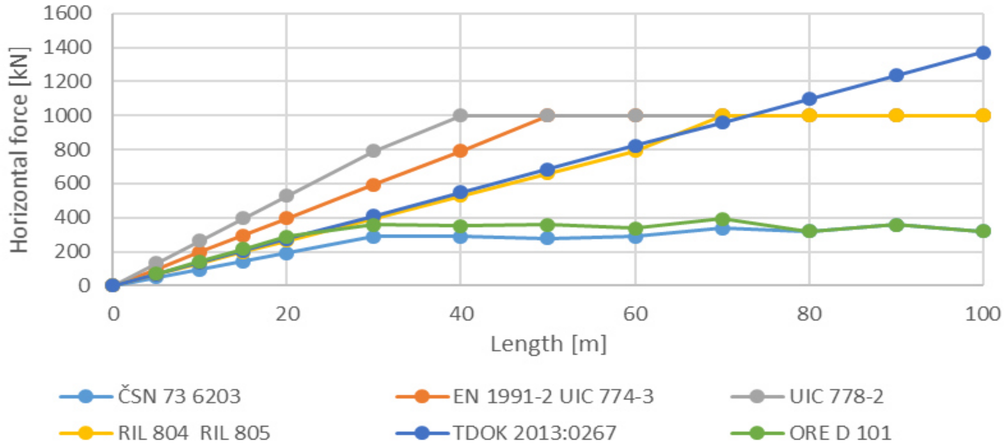

Figure 3. Acceleration forces according to different current and historical codes.

3.5. Action comparison

If we compare the acceleration and braking forces, we can clearly see their value and compare in the Figure 2 and 3. We can see very high variability of the actions.

4. Braking tests results

4.1. ORE D 101 Braking and acceleration forces

The team of specialists consisting of representatives of different European national railway authorities was established in the 1967. The main goal was to solve the issue of estimation of braking and acceleration forces and their distribution over the superstructure, substructure bearings and rails. The assumed variable parameters were: a) structural type of the bridge, b) material of the superstructure, c) bridge span, d) type of bearings, e) railway superstructure and e) rail connections and expansion joints.

One of the outputs is the theoretical model ČSD – Frýba [1]. In the model, the superstructure is defined as a beam element supported at its ends. The rail is replaced by another beam element with free ends continuously connected to the bearing structure and surrounding area by springs. The stiffness of the springs consists of stiffness of connecting elements and stiffness of the rail superstructure. The horizontal load is calculated from the vertical load and friction coefficient. The resulting quantities are forces in rails, bearing structure and bearings.

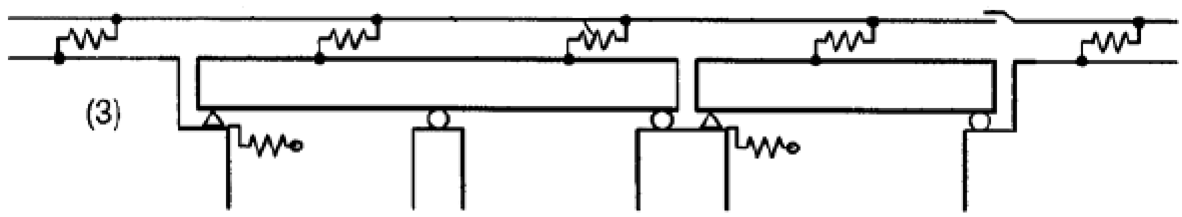

Figure 4. The chart of the quasi-static ČSD – Frýba model.

The most important findings of ORE D 101 research are:

- The maximum braking force occurs shortly before the stopping of the train. The acceleration force grows together with the train thrust.

- The horizontal forces are due to the friction transferred to the rail, bridge, bearings, substructure and surrounding earth. The distribution of forces to different structural members depends on the type of rail connections and expansion joints, length of bridge and type of bearings.
- The influence of structural type, material and rail superstructure has almost no impact on the value of braking and acceleration forces.
- The greatest influence on the value of braking and acceleration forces has the type of the train and adhesion between the braking or accelerating vehicle and the rail.

The value of the vertical force coefficient differs under the given parameters from 0.04 to 0.25. For the most bridges under 50 m the acceleration is the dominant effect and for the bridges over 50 m it is braking.

4.2. The braking test on Losí Bridge

The Losí Bridge is a four-span continuous girder bridge with orthotropic deck and rail bed, placed in the Czech Republic. The bridge transfers a double track. The bridge is supported by pot bearings. The braking test was performed in April 2016. Four electric locomotives Class 230 Laminátka were used for the braking test, each of weight 85 tons. The configuration on the bridge was divided into three cases, single locomotive, four on one track and two on each track. The maximum measured braking force was equal to 17.5 of the acting vertical force [5].

4.3. The braking test on Chotoviny Bridge

The Chotoviny Bridge is a Langer beam bridge transferring double track with welded rails and supported by pot bearings, placed in the Czech Republic. The Langer beam is 100.5 m long. The braking test was performed in 2015, using one locomotive HV740 with twelve Faccpp 9-429.0 wagons and assembly of two HV749 and two HV771 locomotives.

Table 2. The results of braking and acceleration test on Chotoviny bridge [3].

Assembly	Weight [t]	Braking force [kN]	Acceleration force [kN]	Braking force - ratio	Acceleration force - ratio
HV740+Faccpp	1104	525	205	5%	2%
HV771+749	381	920	305	24%	8%

4.4. The braking test on Oskar Bridge

The Oskar Bridge is an arch bridge with box girders, orthotropic deck and rail bed, placed in the Czech Republic close to Austria. There are two same bridges. The arch span is 97.5 m long and carries one track. The bridge us supported by spherical bearings. The bridge is a subject of long term monitoring which started in 2015 and is planned to continue until 2018. The braking test was performed by assembly of two Siemens Taurus ES64U2 locomotives and ten Falls wagons. The maximum measured braking force was equal to 12% of the total weight of the assembly [7].

5. Case study – assessment of Červená Bridge

The Červená Bridge is the perfect example of historical steel railway bridge struggling with calculation of load capacity according to Eurocodes. The bridge was built in 1889 and is a part of the railway track connecting two cities in the southern Czech Republic, Tábro and Písek. The bridge is 254.2 m long with three main spans of 84.4 m, the bearing structure is formed by two truss girders with overall height of 9.9 m and system of cross and longitudinal beams supporting intermediate bridge deck. The rail expansion device is installed on both ends.

Figure 5. The Červená Bridge.

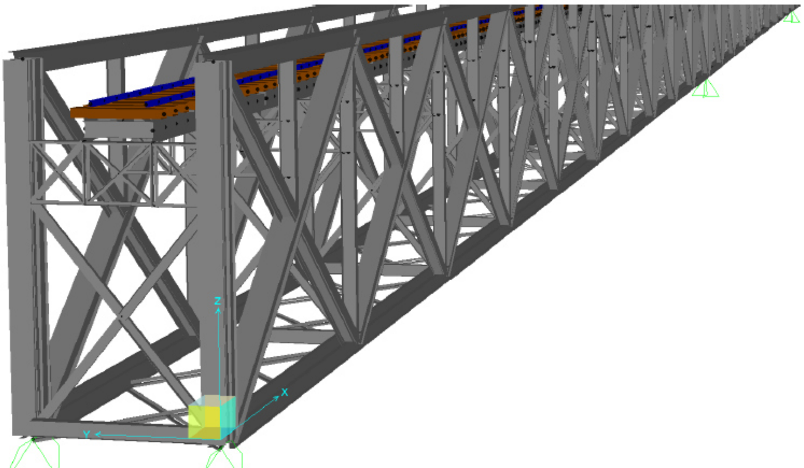

Figure 6. The model of Červená Bridge.

The load capacity calculation was made by SUDOP PRAHA a.s. [4] and the load capacity estimation of this bridge was also the topic of thesis "Static and dynamic behavior of the Červená railway bridge" [6]. In order to investigate the utilization of all structural elements, accurate model was created in both cases. First, the capacity was calculated using the LM71 load model according to Eurocode. The design capacity of the cross beam at the abutment, due to braking forces, was exceeded more than eight times. Different approach was chosen to prove the bridge can at least carry the current traffic. The bridge is located on a local track and therefore, the real traffic model was used. The load train consists of five vehicles each with four 180 kN axels and the braking force was assumed of 20% of the vertical load. Even though, the utilization level of the abutment cross beam was still around 2.1, there was a significant improvement.

The results from the load capacity assessment were taken and used for a simple exhibition of other approaches of braking force calculation. The bridge was assumed to be loaded by LM71 load model from the Eurocode. The safety and combination factors were preserved according to the EN 1990. Only the approach of the braking load model was changed. The results are shown in Table 3.

Table 3. Červená Bridge cross beam utilization level.

Norm	ČSN 73 6203	EN 1991-2 UIC 774-3	UIC 778-2	RIL 804 RIL 805	SIA 269	TDOK 2013:0267	ORE D 101
Braking Force [kN]	2847	5084	5084	4576	4576	3486	2644
Stress – traffic [MPa]	1002.3	1647.6	1647.6	1500.9	1500.9	1186.7	943.7
Stress – overall [MPa]	1176.5	1821.8	1821.8	1675.1	1675.1	1360.9	1117.9
Utilization [-]	5.45	8.44	8.44	7.76	7.76	6.30	5.18

Even though the cross beam does not still satisfy the design checks, the table shows very significant impact of the brake/acceleration model on the overall load capacity of the bridge. Also, the conservativeness of the Eurocode is evident.

6. Real traffic model proposal

The real traffic data on the whole railway network of the Czech Republic were provided by the Czech railway maintenance authorities SŽDC. The data contain of traffic during June and November on all track sections owned by SŽDC. These months were chosen due to lower cargo traffic during summer months and higher cargo traffic at the end of every year. Therefore, combined data from these two months should be sufficient to affect the whole year and to form the accurate real traffic model.

The data provide information about the type of locomotive, the total number of axels, weight and length of the whole train assembly. The evaluation of these data can be used to determine the year frequencies of train assemblies of certain type on each track per year. Combined with the data about locomotive braking and acceleration forces, the normative theoretical models and real in-situ measurements, real traffic model can be created for the whole Czech railway network. Evaluation of the data for every single track of the railway network would be too complex. Therefore, the track classes can be used for such a purpose. The Czech railway network is divided into seven classes by SŽDC based on the amount of gross transported tons per year. Such dividing criterion can accurately secure separation of local tracks with low traffic importance used only for public transportation purposes and heavily used tracks for cargo transport.

7. Conclusion

The review of historical and current used national codes has provided useful information about the determination of braking and acceleration forces. Together with the data obtained from several in-situ measurements of these actions it creates a clear idea how Eurocodes can be conservative especially for load capacity calculation of existing bridges. Moreover, the Eurocodes consider the design service life for bridges of 100 years, where some of the old bridges are assumed to be in service for maximum ten to twenty years.

In order to be able to preserve these bridges and not to lower their allowable capacity, the braking and acceleration forces effects should be in some cases reduced. The combination of real traffic loading and reduced braking forces can lead to significant improvements in load capacity assessment and historical bridges such as Červená Bridge can be used for another several years before the necessary funding is secured for either the bridge reconstruction or the structure replacement.

For such purpose the real traffic model should be created, providing the useful information about the trains and frequencies on each of the seven railway track classes in the Czech Republic.

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