Fatigue design in reinforced concrete bridges according to Brazilian code

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Abstract

There has been an increase in the flow of freight vehicles commuting on Brazilian highways. Then, special attention to the structural performance of bridges regarding the fatigue in beams is needed. Brazil has neither normative metrology to study real data flow of vehicles, nor specific fatigue load train models and coefficients to the analysis and design of road bridges. The same load train that is used for general dimensioning, TB 450, is used for the fatigue verification. Hence, this work aims to verify if the current TB 450 is representative of the freight heavy vehicles with 2 to 9 axles concerning the effects of fatigue in the longitudinal reinforcement of beams of theoretical reinforced concrete bridges with two, three, and five beams. This verification is performed analyzing the stress variations found in the longitudinal reinforcement of vehicles with 2 to 9 axles and the TB 450. Based on the results, the longitudinal steel reinforcement was more susceptible to fatigue's effects. Freight vehicles with 5, 6, 8 and 9 axles presented the most significant stress, therefore, they tend to cause more deleterious effects. Hence, the adoption of a Brazilian normative fatigue specific load train and coefficients is necessary to analyze pre-existing road bridges and design new ones most accurately.

Keywords: Fatigue; Longitudinal Reinforcement; Reinforced Concrete Bridges; Stress Variations; Brazilian Normative Load Train;

1. Introduction

Currently, Brazil presents road modal as the predominant one. According to the Brazilian National Transport Confederation (CNT, 2020), road freight transport corresponds to 61.1% of the total. This fact has a significant impact on Brazilian bridges and viaducts. Among the structural problems to which these structures are susceptible, fatigue needs to be highlighted (Pimentel, Bruhwiler e Figueiras, 2008; Baroni, Silva Filho, Gastal, 2009) because the variability and the regime of live loads make bridges and viaducts more prone to suffer from this phenomenon.

According to Nowak and Fischer, (2016), the traffic infrastructure guarantees not only greater economic efficiency, but also allows people to get around well, thus contributing to the development and wealth of any country. In this context, bridges play an important role due to its responsible for crossing obstacles and connecting places (Gonzalez et al., 2019).

Researchers around the world have been conducting studies about the phenomenon of fatigue in road bridges and viaducts (Pimentel, Bruhwiler e Figueiras, 2008; Baroni, 2010; Pircher et al. 2011; Albuquerque, Pfeil, 2012; Zhang, Xin, Cui, 2012; Osumeje et al. 2016; Junges, 2017; Deng, Yan, 2018; Braz et al. 2018, LU et al., 2017; Liu ,Zhou, 2018; Lou; Nassif; Su, 2017; Alencar et al., 2018; Mascarenhas, Carvalho, 2019, Hassen, 2020, Pillai, Talukdar, 2020). Those studies are justified by the relevance of these structures in the flow of people, products and goods; the high age of the bridges and viaducts; and the heterogeneity of freight vehicles that commute in railways.

The American Code LRFD Bridge design specifications (AASHTO, 2015), defines fatigue as "a phenomenon of material failure caused by repeated applications of a load. When applied infrequently, these loads would cause no undesirable effects, but when applied repeatedly, they can lead to failure" (AASHTO, 2015).

When the fatigue is analyzed, certain concepts and variables are relevant. The fatigue process in the longitudinal reinforcement of beams is a function of the dead loads and vehicles commuting (the live loads), the type of reinforcement used, and the stress variations.

In Brazil, there are two Codes with instructions and guidelines about the design and dimensioning of concrete bridges and viaducts, the ABNT NBR 7188:2013, "Road and pedestrian live loads on bridges, viaducts, footbridges and other structures" (ABNT, 2013) and the ABNT NBR 6118:2014, "Design of concrete structures – procedure" (ABNT, 2014).

Due to the variability and the regimen of occurrence of live loads, both national and international codes use different live load models to the design of bridges and viaducts. The current ABNT NBR 7188:2013 presents the vehicle called TB 450, with six wheels and a total weight of 450 kN, as the current normative live load model.

International codes for bridges such as the European, "Eurocode 1: Actions on Structures – Part 2: Traffic Loads on Bridges" (2002), American, "AASHTO LRFD Bridge Design Specifications" (AASHTO, 2015) and the Chinese, "Code for design of highway reinforced concrete and prestressed concrete bridges and culverts" (2004) have particular live load model vehicles and specific coefficients for the analysis and design of bridges on the aspect of fatigue. However, Brazil has neither specific load train models nor coefficients to the analyzes and designs of road bridges and viaducts under fatigue. The same load train that is used for general dimensioning is used for fatigue verification. Also, the Brazilian bridge and viaduct codes have neither presented instructions nor methodologies on how to investigate, analyze, and design any bridges using the data from the real flow of freight vehicles.

This issue can put the Brazilian bridge codes at a disadvantage in terms of performance and safety of the bridges, compared to international ones. According to Braz et al. (2018), regarding the fatigue design and its effects in the reinforcement, the Brazilian code has shown to be less conservative than the European one. Furthermore, the authors (2018) advocate that it occurs because the European code has a rigor, presenting both specific coefficients and load train vehicles to design, and it has a unique value of fatigue resistance to all diameters of the steel reinforcement bars.

Carneiro and Bittencourt (2018) state that in the analysis of existing bridges, the Brazilian bridge codes lack the dynamic analysis presented in the European code, and specific coefficients of impact presented in the code of United States. This statement converges to what is explained by Stucchi and Luchi (2015), who remarks that the load train models used in Brazilian bridge standards are just copies of German standards, and there is no considerable effort to present "a genuine live load model born in Brazilian lands".

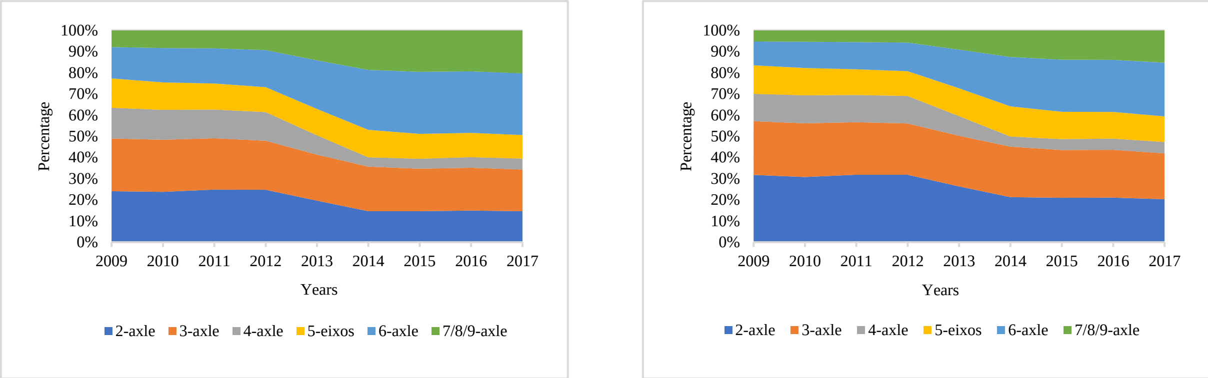
Thus, it is imperative to continuously check if the current Brazilian normative load model is representative to be used in the design of new bridges and viaducts, and the structural recovery of ancient ones, regarding the fatigue phenomenon, given the current traffic composition on the Brazilian highways.

1.1 Objectives

This work aims to analyze whether the Brazilian normative live load model, TB 450, can represent the flow of real heavy vehicles regarding the effects of fatigue on longitudinal reinforcement in reinforced concrete beams of bridges. Theoretical bridge models were designed, and road freight vehicles with 2 to 9 axles were used. Such verification is performed analyzing the calculated stress variations found in the longitudinal reinforcement due to the vehicles with 2 to 9 axles and the TB 450.

1.2 Justifications

The annual number and weight of freight vehicles have increased around the world (Pircher et al. 2011; Han et al. 2015; Deng, Wang, Yu, 2016; Han et al. 2017) and on Brazilian highways (Mascarenhas, Carvaljo, 2019; CNT, 2019; Sindipeças, 2018). Regarding the road traffic in Brazil, since 1990, the circulating fleet of trucks has shown significant growth. Data on the number of freight vehicles from two different highways in the state of São Paulo in Brazil, collected from toll collection points (TCP) demonstrate this. TCP 01, which is based in the city of Limeira, had an increase of 7.68% between 2009 and 2017. TCP 02, based in the city of Valinhos, had an increase of 8.68% in the traffic of freight vehicles. TCP 01 and TCP 02 had significant growth in the number of vehicles with 5 to 9 axles since 2014, as shown in figure XX (a) and (b), respectively.



(a) (b)

Figure 1 – Vehicle percentages

Jang and Mohammadi (2017) claim that the damage related to fatigue can be more critical in older bridges since they were designed and built using normative load models established for a lower volume of truck traffic than the one on highways currently. Brazil has a considerable number of bridges and viaducts, and most of them were designed using previous live load models. Brazilian authorities and governmental bureaus do not have a clear understanding and sufficient information about the real and current situation of these structures (Mascarenhas, Carvalho, Vitório, 2019).

Rossigali et al. (2015) point out that the current Brazilian live load model to design bridges (ABNT, 2013) does not represent the current traffic effects properly, and it can be in certain situations against security.

Maintenance of ancient and current railway bridges require that they can support more gigantic traffic volumes and higher traffic loads and train speeds (Pimentel, Bruhwiler e Figueiras, 2008). Hence, studies and analyzes, such as the one carried in this work, are necessary to provide the design of new bridges most economically and safely in terms of design and service life, and to those existing bridges, studies like this one are necessary to analyze the structures fatigue safety.

The frequent traffic of heavy vehicles causes problems in the load-carrying efficiency of bridges and fatigue damage, and Deng and Yan (2018) state that those issues are commonly ignored. This negligence can generate severe consequences since the dynamic actions (live loads) that act on bridges and viaducts can increase the internal failures or even contribute to the propagation of cracks and fractures Leitão et al. (2011), which may cause them to collapse. This statement converges to the conclusions presented by Osumeje et al. (2016), who explain that the deleterious fatigue effects in beams of reinforced concrete bridges are a grave issue regarding the durability; thus, it cannot overlook.

The mechanical behavior of reinforced concrete elements is linked to the behavior of the reinforcement steel. Then, the rupture of the element is associated with the rupture of the reinforcement, which most often occurs under flexure. Thus, the failure in the steel reinforcement due to fatigue deserves special care and attention.

2. Fatigue according to the Brazilian Code NBR 6118:2014

The phenomenon of fatigue is related to "repeated dynamic actions" under a structural member, and those actions cause "progressive and permanent modifications of the internal structure of a material subject to the oscillation of tensions resulting from these actions" (ABNT, 2014). Dineshkumar and Ramkumar (2020) explain that reinforced concrete structures were made to handle static loads, but in the practice, those structes are continuously under cyclic loads, such as fatigue.

There are different methodologies to analyze the effect of fatigue on materials, among them the Paris-Erdoga Law, Mechanics Fracture, and the principle or mechanics of Cumulative Damage, or Palmgren-Miner rule (Brighenti, Carpinteri, Corbari, 2013). Keerthana and Chandra Kishen (2018) highlight the importance of the last two approaches when stating that they have been widely used by the scientific community to study the fatigue behavior of structures.

The principle of Cumulative Damage was chosen to be used to study the stress variations. This approach was adopted because in bridge fatigue non-uniform stress variations occur; it is recommended to a reduced number of structural members, such as beams; it has mathematical rigor, given the absence of conversion and simplification formulas; and it has been used by several authors in the national and international literature (Pimentel, Bruhwiler, Figueiras, 2008; Santos, Pfeil, 2014; Freitas, 2014; Zhang, Xin, Cui, 2012; Wang et al., 2015; Mascarenhas, Carvalho, 2019; Hassen, 2020).

As stated in the introduction, the stress variation is one of the most critical aspects when the fatigue analyses are carried out in beams of reinforced concrete bridges. Then, the verification of the TB 450 to fatigue is performed by comparing, in each theoretical model of bridge studied, the TB 450's stress variation $\Delta\sigma$ of the longitudinal reinforcement with the variations obtained for the real vehicles from 2 to 6 axles.

Before calculating the stress variation, it is necessary to determine both maximum and minimum stresses in the reinforcement. To calculate the stress, first, it is necessary to determine the bending moment in the middle of the span of the beams. Then, in order to do that, the software Ftool (Two-dimensional Frame Analysis Tool) was used. Once this was done, it was necessary to perform the combination of these moments following the recommendations of ABNT NBR 6118:2014 (ABNT, 2014).

The bending moments in the middle of the span in each beam from TB 450 and vehicles of 2 to 9 axles were increased by the Brazilian normative coefficients (Equation 1): Vertical impact coefficient (CIV), the number of traffic lanes coefficient (CNF) and the additional impact coefficient (CIA); the initials stand for the names in Brazilian Portuguese (ABNT, 2013). In this paper, they were called by Weighting Coefficient of Vertical Live Loads ($WCVL = CIV.CNF.CIA$), and the values change according to the bridge span. Bridge with 10.0, 15.0 and 20.0 m have WCVL equal to 1.35, 1.33 and 1.27, respectively.

$$M_{qk} = WCVL.M_q \tag{1}$$

ABNT NBR 6118:2014 (ABNT, 2014) establishes that the verification of fatigue in bridges is done by determining the frequent combination of actions, and the process of Cumulative Damage can be used for the fatigue analyses and estimation in beams of bridges. Then, the frequent combination of the maximum design normative moment to the TB 450 is given by Equation 2, and to the real vehicles of 2 to 9 axles is given by Equation 3:

$$M_{d,\max\_TB450} = \sum_{i=1}^{m} M_{gik} + \psi_1.M_{qk} \tag{2}$$

$$M_{\max\_axles} = \left(\sum_{i=1}^{m} M_{gik} + .M_{q1k} \right) \tag{3}$$

Where: $M_{d,\max\_TB450}$ and $M_{d,\max\_axles}$ are the design value of the maximum bending moment in the combinations to the Service Limit State to the TB 450 and the vesicles with 2 to 9 axles, respectively; M_{gik} are the dead loads; M_{qk} are the live loads; ψ_1 is the frequent combination reduction factor, being equal to 0.5 for beams.

Moreover, the minimum design normative moment to all vehicles is given by Equation 4:

$$M_{d,\min} = \sum_{i=1}^{m} M_{gik} \tag{4}$$

Where: $M_{d,\min}$ is the design value of the minimum bending moment in the combinations to the Service Limit State.

Once both maximum and minimum design moments are determined, the maximum and minimum stress in the reinforcement can be calculated by the following Equations 5 and 6, respectively:

$$\sigma_{s,\max} = \alpha_E . \frac{M_{d,\max} . x_i}{I_{II}} \tag{5}$$

$$\sigma_{s,\min} = \alpha_E . \frac{M_{d,\min} . x_i}{I_{II}} \tag{6}$$

$\sigma_{s,\max}$ is the maximum stress in the reinforcement; $\sigma_{s,\min}$ is the minimum stress in the reinforcement; x_i is the distance from the neutral axis until the inferior surface; α_E is the quotient of the elasticity modules of reinforcement and concrete; I_{II} is the moment of inertia at Concrete Stage II.

Hence, stress variations in the steel reinforcement can be calculated using the following Equation 7:

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min} \tag{7}$$

Since this paper uses symmetric "T" beams in all bridge models, Figure 2 presents the "T" beam used and a generic stress distribution, representing the steel reinforcement stress variation, and the maximum and minimum ones.

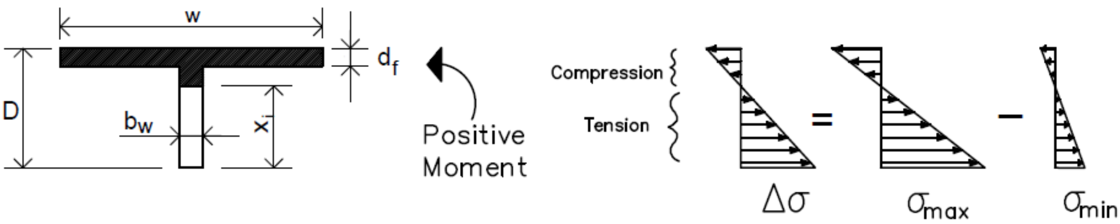


Figure 2 – Generic stress distribution in the studied "T" beam

Therefore, in this work, the TB 450 was considered representative of the real vehicles that commute on the Brazilian highways here analyzed in terms of fatigue if the stresses variations calculated for these real vehicles were smaller than those found for the TB 450. Figure 3 summarizes these considerations.

TB 450 was considered verified if $\Delta\sigma_{TB450} > \Delta\sigma_{vehicles\_n\_axles}$

TB 450 was considered not verified if $\Delta\sigma_{TB450} < \Delta\sigma_{vehicles\_n\_axles}$

Figure 3 – Considerations to validate TB 450

n represents the analyzed vehicle according to their numbers of axles, from 2 to 9.

In addition to that, the ABNT NBR 6118:2014 (ABNT, 2014) establishes that the steel reinforcement must be verified regarding the fatigue phenomenon. According to the Brazilian Code, this verification is satisfied if the maximum stress variation calculated, $\Delta\sigma$, for the combination of frequent loads satisfies Equation 8:

$$\gamma_f .\Delta\sigma \leq \Delta f_{sd,\,fad} \tag{8}$$

γ_f is the coefficient for unfavorable loads, and the case of reinforced concrete bridge beams it is equal to 1.0; $\Delta f_{sd,\,fad}$ is the maximum normative stress variation, in MPa, according to the steel reinforcement bar diameter, in this case, it is equal to 17.5 kN/cm^2.

Based on that, the steel reinforcement area must be increased by the fatigue coefficient k (Equation 9) whenever $\Delta f_{sd,\,fad}$ is smaller than $\Delta\sigma$. It is mentioned that all steel areas met the normative criteria of ABNT NBR 6118:2014; therefore, it was not necessary to use the k coefficient.

$$k = \frac{\Delta\sigma_s}{\Delta f_{sd,\,fad}} \tag{9}$$

3. Materials and Methods

Three theoretical models of reinforced concrete bridges with different structural systems were used, and all of them have the following nomenclature __B__T RC__, where B represents the number of beams, T de number of cross grinder per bridge, and RC means that the beams and the bridges are made of reinforced concrete. Two, three, and five beam bridges with different spans are used per each bridge deck.

All the nine studied bridges are simply supported, and their designs follow the specifications from the "*Manual de Projeto de Obras-de-Arte Especiais*", which is a guide written and established by the National Department of Transport Infrastructure (DNIT) of Brazil (DNER, 1996). Moreover, using the information about the characteristics of the Brazilian bridges stock contained in the DNIT (2018) database, it was made the design of these bridge models. Figure 5 shows the cross-sections of the bridges with two, three, and five beams.

All the theoretical bridge models are symmetric, and it was chosen to avoid unnecessary calculus and analysis. In other words, for bridges with two beams, the entire analysis performed for beam 1, B1, are considered the same for beam 2, B2. In the case of the bridges with three beams, the analysis of beam 1, B1, are the same as beam 3, B3, and it is necessary to carry out the analysis about beam 2, B2. In the case of the bridges with five beams, the calculations for beam 1, B1, are the same as beam 5, B5; for beam 2, B2, are the same as for beam 4, B4, and it is carried out the analysis for beam 3, B3.

Furthermore, in the design of the bridges, two traffic lanes were assumed, and each strip has of 3.60 m of width (7.20 m in total), plus two shoulders in each side with 2.40 m each, following the recommendations from the Brazilian Gaudiness "*Manual de Projeto Geométrico de Travessias Urbanas*" (DNIT, 2010).

The beams of the bridges presented symmetric cross-section in "T" (Figure 2), and they have the dimensions, as shown in Table 1, according to ABNT NBR 6118:2014 (ABNT, 2014). The concrete compressive strength used has an f_{ck} of 35 MPa, and the reinforcement steel had f_{yk} of 500 MPa of yield stress, and the diameters of the bars ϕ are equal to 25 millimeters.

Table 1 –Geometry adopted of the RC beam cross section for the examples

Bridge	2B 1T RC 10	2B 1T RC 15	2B 1T RC 20	3B 0T RC 10	3B 0T RC 15	3B 0T RC 20	5B 0T RC 10	5B 0T RC 15	5B 0T RC 20
b_w (cm)	35	35	35	35	35	35	35	35	35
w (cm)	235	335	435	235	335	350	200	200	200
d_f (cm)	30	30	30	30	30	30	30	30	30
D (cm)	100	150	200	100	150	200	100	150	200

The cross-sections of internal and external beams present the same dimensions. Moreover, since in this work the dynamic analysis of vehicle loads on the bridge is not done directly, but through the use of coefficients from the Brazilian code that simulate this dynamic effect, only the effects caused on the beams alone are studied. Therefore, it is not considered, for example, the types and effects of the bridge bearings. Tables 3, 4 and 5 show the cross-sections (A_c), in cm^2, moments of inertia in State II (I_{II}), in cm^4, and reinforcement areas (A_s), in cm^2, of all bridge model beams.

Table 2 – Characteristic values of 2-beam bridges

Bridge	2B 1T RC 10	2B 1T RC 15	2B 1T RC 20
	B1/B2	B1/B2	B1/B2
A_c	9500	14250	19000
I_{II}	4578445	15239180	35738242
A_s	106.9	137.0	166.7

Table 3 – Characteristic values of 3-beam bridges

Bridge	3B 0T RC 10		3B 0T RC 15		3B 0T RC 20	
	B1/B3	B2	B1/B3	B2	B1/B3	B2
A_c	9500	9500	14250	14250	16450	16450
I_{II}	3655139	2384790	12008677	8114298	27545509	18731747
A_s	82.6	49.6	104.3	67.1	127.8	83.3

Table 4 – Characteristic values of 5-beam bridges

Bridge	5B 0T RC 10			5B 0T RC 15			5B 0T RC 20		
	B1/B5	B2	B3/B4	B1/B5	B2	B3/B4	B1/B5	B2	B3/B4
A_c	8450	8450	8450	10200	10200	10200	11950	11950	11950
I_{II}	2349799	2019698	2195810	7414837	7080892	6154192	17181223	15234170	14555375
A_s	50.3	42.0	46.4	64.7	55.5	52.4	80.6	70.4	66.9

Since the fatigue life is determined using the cumulated damage methodology, the bending moments due to the flexure in the reinforced concrete beams need to be calculated, and they are analyzed in the middle of the span. Because the most critical loads on bridge's beams in the fatigue analysis are the live ones, the influence lines technique is used to obtain the support reactions and internal stresses in bridge's beams with two and multiple beams. In the case of multiple-beam bridges, it is also used the Fauchart Process, which can be found in various publications, such as Stucchi (2016), Trentini, Martins (2015), Moura et al. (2016), Basso, Carvalho, Faria, 2017 e Mascarenhas, Carvalho, 2019.

The software Ftool (Two-dimensional Frame Analysis Tool), which makes 2D structural analysis and uses the Direct Rigidity Method for the analysis, was used (Ftool, 2018). Several authors have used Ftool to carry out their structural analysis of live loads in beams of bridges, such as Mascarenhas, Carvalho, 2019; Rota Oeste S.A (2016), Baroni, 2010, Santos, Perlingeiro, Alves (2017), Turmina (2016), Medeiros (2018), Drun, Souza (2018) e Mascarenhas, Christoforo e Carvalho (2020).

3.1 Determination of the normative live load model, TB 450

The Brazilian live load model TB 450, from ABNT NBR 7188:2013 (ABNT, 2013), has six wheels and occupies an area of 18.0 m^2, as shown in Figure 4, where p is the portion of the uniformly distributed load, and it is 5 kN/m^2, and P are the concentrated loads on the wheel axles of the live load model, and it is 75 kN.

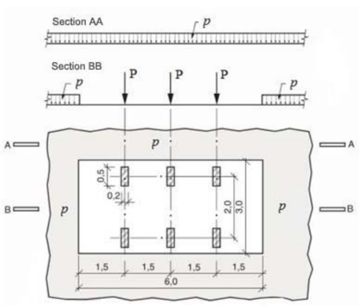
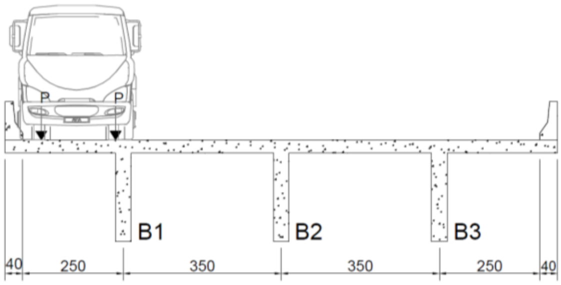


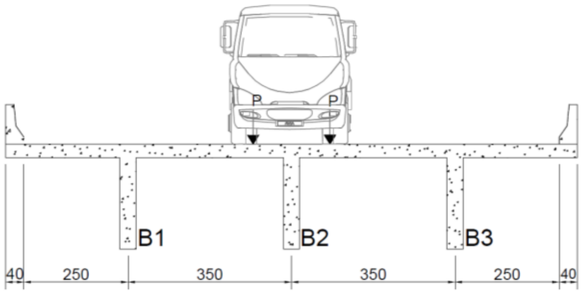
Figure 4 – Live load model according to ABNT NBR 7188:2013

The live load model TB 450 must be placed along the entire cross-section of the bridge where there is a road lane, providing the wheels are in the most unfavorable position. Figure 5 shows the most unfavorable positions for all bridge models.

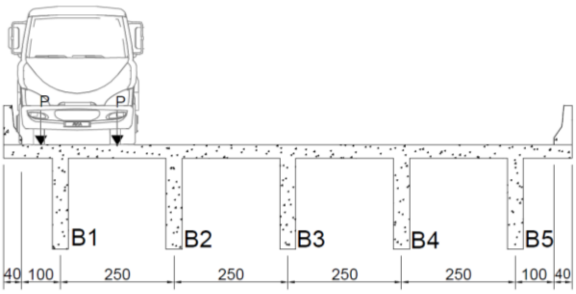
2-beam bridge



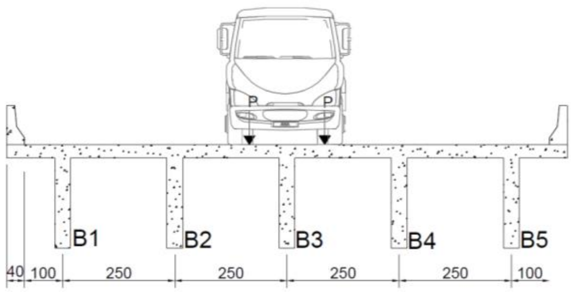
3-beam bridge – Beam B1



3-beam bridge – Beam B2



5-beam bridge – Beams B1 and B2



5-beam bridge – Beam B3

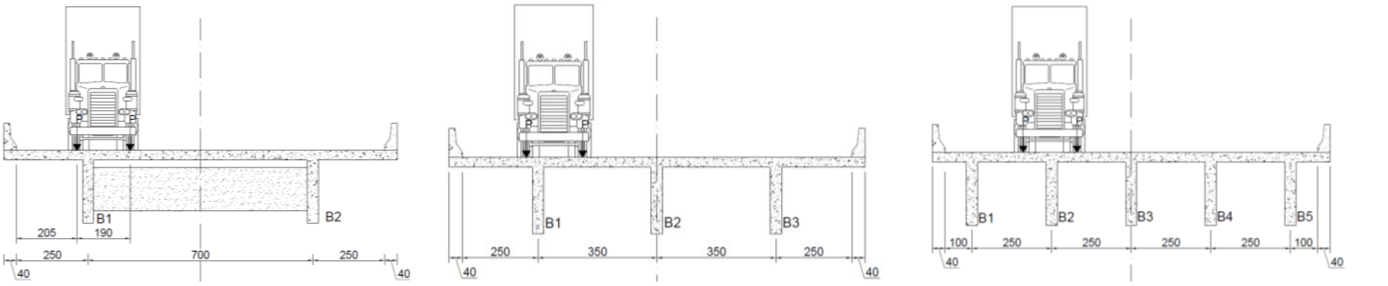
Figure 5 – TB 450 on the cross-section for the maximum stress situation – dimensions in cm

3.2 Loads for real freight vehicles

When the fatigue phenomenon is studied, it is necessary to know the position in which the freight vehicles travel on the roads. Due to the heterogeneity of the vehicles, their size variety, and the positions that they commute over the service life of the bridge structures, different internal forces can be caused in the beams depending on the vehicles are. Several kinds of research were carried out to establish the most common position of the vehicles on the road. The Eurocode 1 (2002) advocate that half of the actual vehicles (vertical loads) that travel on the highways are centered on the traffic lane, and the others are distributed symmetrically along the lane.

Hence, in this work, it was considered that 100% of the freight vehicles here analyzed commute in the center of the traffic lane because this adopted position was representative, and other authors assumed it, Albuquerque and Pfeil (2012), Santos and Pfeil (2014) and Mascarenhas and Carvalho (2019). In addition to this, the following considerations about the freight model of real vehicles were assumed:

I. The procedure for determining both maximum and minimum bending moments from the real vehicles was the same used for the TB 450; however, the real freight vehicles were positioned as shown in Figure 6 (a) (b) (c) for 2-beam, 3-beam and 5-beam bridges, respectively;



(a) (b) (c)

Figure 6 – Transverse position adopted for freight vehicles - dimensions in cm

II. Crosswise the vehicles have the same dimensions, with 1.90 m from axle to axle (Figure 6). Longitudinally, the dimensions and load values adopted are those shown in Figure 12, following the recommendations from the Brazilian National Transit Council (CONATRAN), which is applied by DNIT (2012);

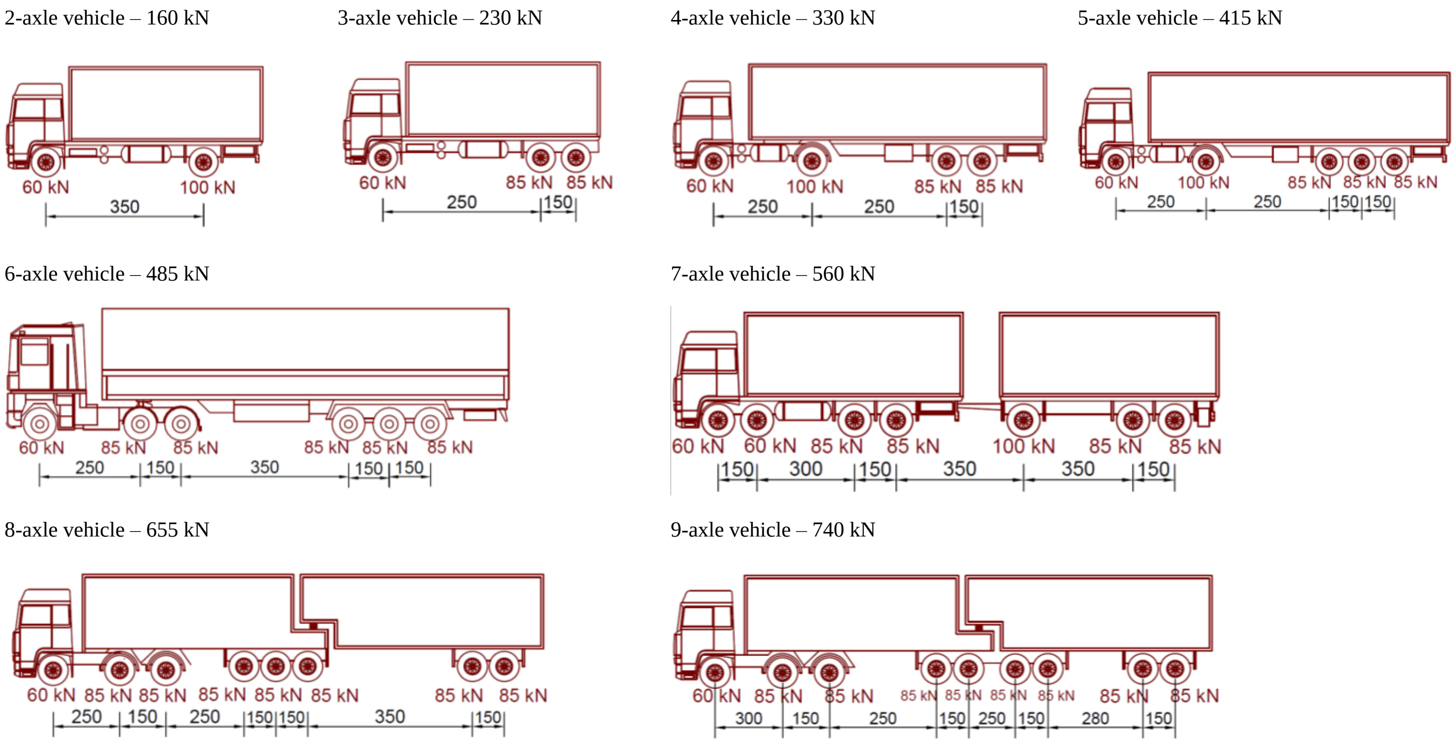


Figure 7 – Representation of 2 to 6 axle freight vehicles

III. 100% of the real freight vehicles are placed in the centerline of the traffic lane, and it was taken into consideration only one freight vehicle commuting on the bridge, as assumed by Mascarenhas and Carvalho (2019).

4. Results and Discussion

The stress variations had an essential role in fatigue life estimation; then, the following analyzes were performed by comparing the stress variation of the TB 450 and with the ones from the real vehicles of 2 to 9 axles for all bridge models. The results were presented according to the type of bridge. The steel reinforcement areas of all beams were verified regarding fatigue using Equation 8, and all of them satisfy what is stated by the Brazilian standard.

Orange horizontal lines represented the values found for the TB 450, and the real vehicle stress variations were presented using blue lines. Figure 8 (a) (b) and (c) show the values of stress variations in the longitudinal reinforcement for 2-beam bridges of 10, 15 and 20 m, respectively.

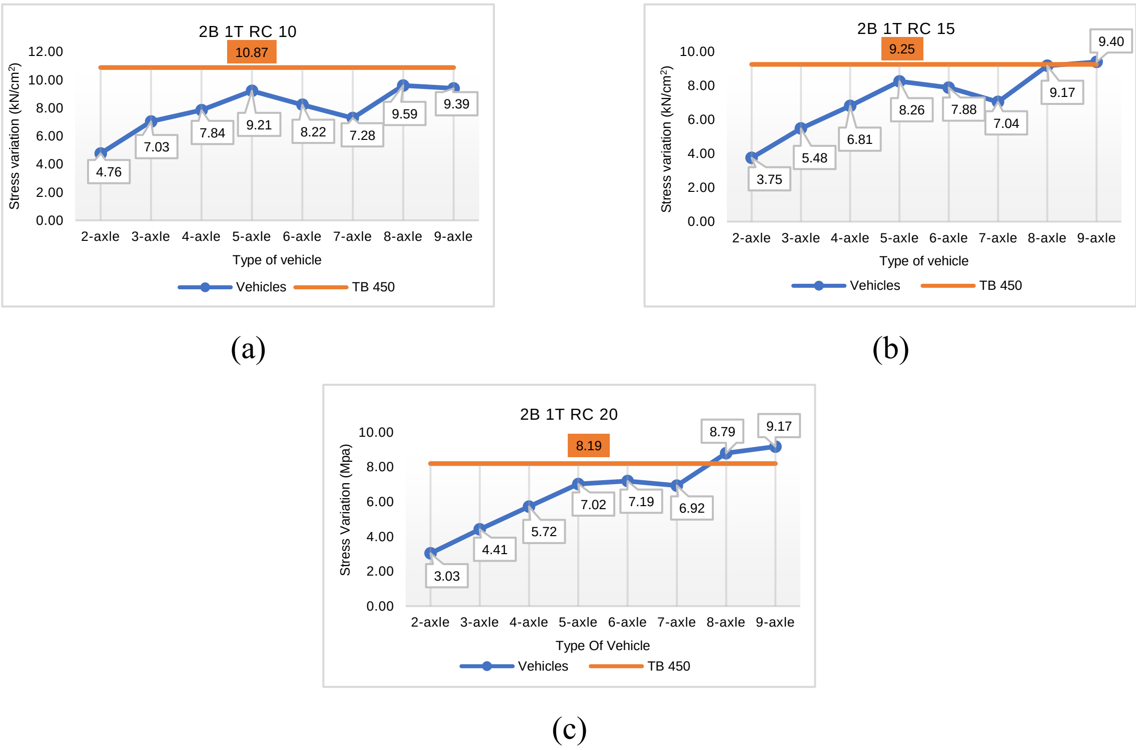


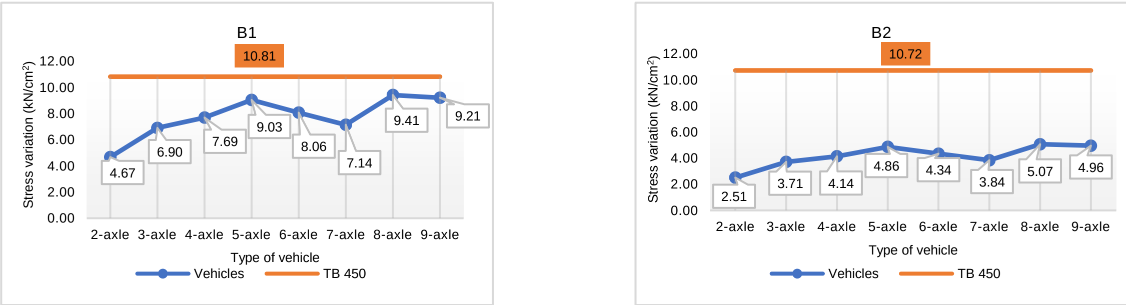
Figure 8 – Stress variations found for bridges with two beams

According to the results, in the three models of bridges, vehicles with 5, 6, 8 and 9 axles were the most critical ones, mainly the 9-axle vehicle. Even though all the stress variations found for the freight vehicles for the bridge 2B 1T RC 10 were not higher than the one from the TB 450, vehicles with 5, 8 and 9 axles were close to it.

In the case of the bridge 2B 2T RC 15, the vehicles with 9 axles presented stress variation over than the one calculated using the TB 450; it was 1.60% higher; therefore, TB 450 was not verified for those that vehicle. Moreover, the 5 and 8 axle vehicles had stress variation close to the one from the TB 450.

For the 2B 3T RC 20 bridge, 8 and 9 axles vehicles presented huger stress variation than the TB 450, and they were, respectively, 6.83% and 10.69% bigger than TB 450, so for those vehicles, TB 450 can be considered not verified. In that bridge model, the vehicles with 5, 6 and 7 axles also had stress variations close to the limit.

After that, the bridge models with three beams are analyzed. The stress variation found for B1 and B2 of 3B 0T RC 10 bridge is shown in Figure 9 (a) and (b).

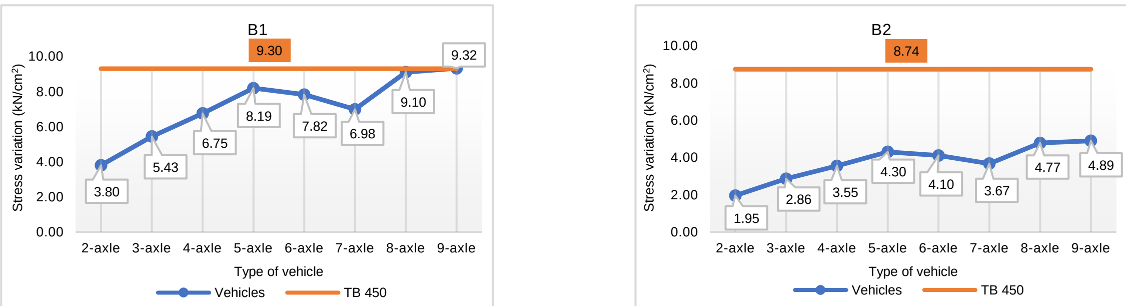


(a) (b)

Figure 9 – Stress variations found for bridges with three beams – 3B 0T RC 10

Analyzing the results from Figure 9, it was possible to conclude that for both beams, B1 and B2, the vehicles stress variations were smaller than those found using the TB 450, then TB 450 can be considered verified for them. Besides, beam B1 presented the highest stress variation when it was compared to beam B2, which has average stress variation of the real vehicles around 61% less than the TB 450. Although the stress variations were within the limit in both beams, vehicles with 5, 8 and 9 axles were those that have the highest stress variation.

Figure 10 (a) and (b) describes the results found for the stress variations for bridges with three beans 3B 0T RC 15, for beams B1 and B2, respectively.

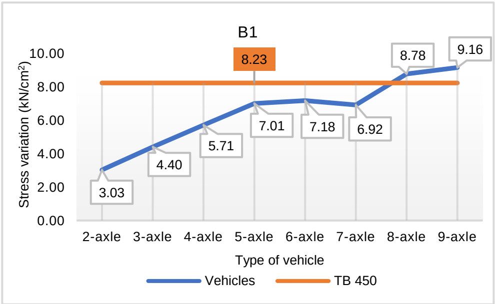


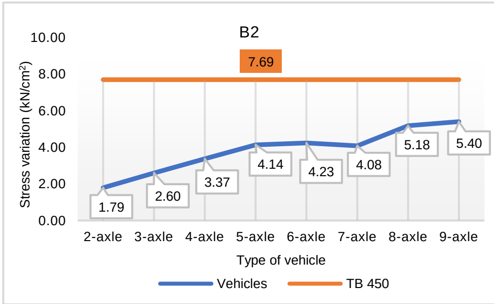
(a) (b)

Figure 10 – Stress variations found for bridges with three beams – 3B 0T RC 15

According to Figure 10 (a), it can be seen that B1 has the highest stress variation, and vehicle with 9 axles exceeded in 0.21% the stress variation of TB 450. Also, in both beams, 5, 8 and 9-axle vehicles are the most prejudicial ones.

Figure 11 (a) and (b) show the results found for stress variations for the bridge 3B 0T RC 20, for beams B1 and B2, respectively.



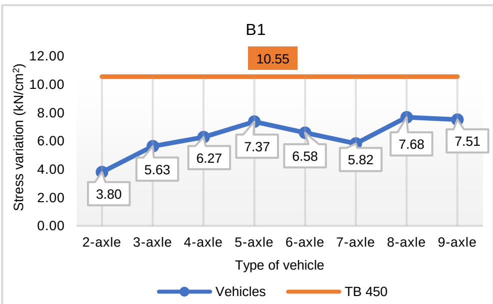


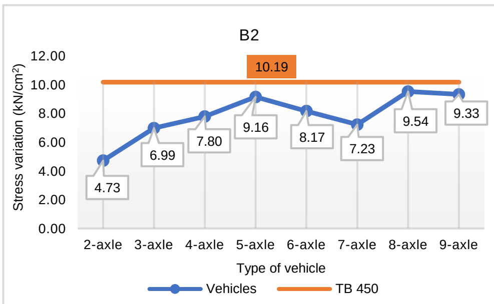
(a) (b)

Figure 11 – Stress variations found for bridges with three beams – 3B 0T RC 20

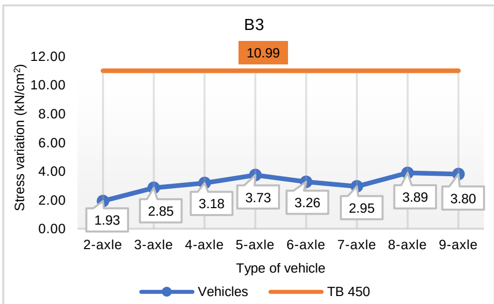
Analyzing the results obtained above, it was noted that in B1, 8 and 9-axle vehicles were over the limit of stress variation of TB 450, 6.26% and 10.15% higher; thus, TB 450 was considered not verified for those. Secondly, B2 presented all the stress variations within the TB 450 limit. Likewise, in the previous bridges, real vehicles with 5, 6, 8 and 9 axles had the highest stress variation in both beams.

Finally, the stress variation calculated for bridges with five beams were analyzed. First, the values for stress variations for the bridge 5B 0T RC 10 were presented in Figure 12 (a), (b) and (c), respectively for beams B1, B2 and B3.





(a) (b)

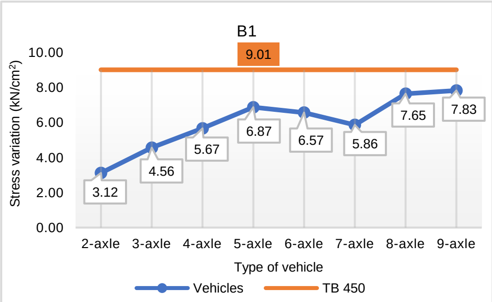


(c)

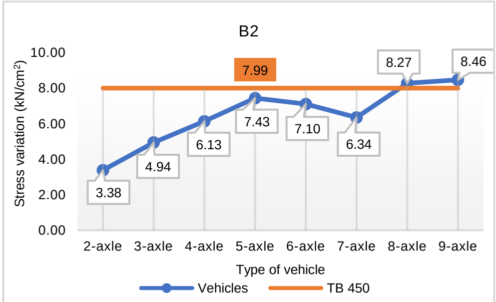
Figure 12 – Stress variations found for bridges with five beams, 10 m span – 5B 0T RC 10

Based on the results from Figure 12, all three beams had the vehicles' stress variations in the reinforcement within the limit stated by their respective TB 450. Also, if we categorize the three beams in ascending order of stress variation, from the lower to the higher, the order is: B3, followed by B1, and then by B2. Although the stress variations due to the real vehicles found in B2 were smaller than the one from TB 450, three of them were significantly closer to the limit, which leads to understanding that overload trucks can easily present stress variations huger than the TB 450. Once again, in all beams, the vehicles with 5, 8 and 9 axles had the most expressive stress variations.

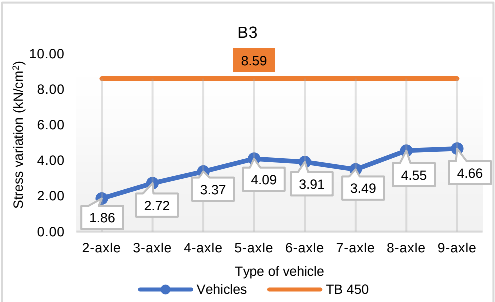
The results obtained for the bridge 5B 0T RC 15 were presented below for beams B1, B2 and B3, respectively, through Figure 13 (a), (b) and (c).



(a)



(b)

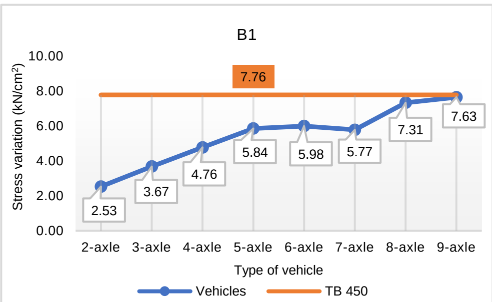


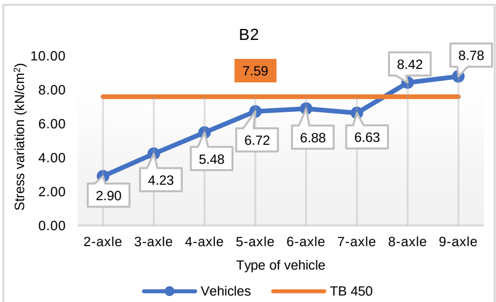
(c)

Figure 13 – Stress variations found for bridges with five beams, 15 m span – 5B 0T RC 15

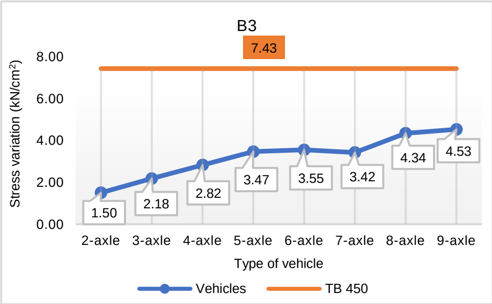
The results found for 5B 0T RC 15 were similar to those obtained to 5B 0T RC 10 in two points. Firstly, beam B3 had the lower stress variation being around 60% less than the TB 450, and beam B2 had the highest ones. Secondly, vehicles with 5, 8, and 9 axles were those with superior stresses compared to the others. B2 presented two vehicles whose stress variation were over the TB 450 limit: 8-axle, which was 3.39% bigger, and 9-axle, which was 5.56% higher than the stress variation from TB 450. Then it was considered not verified for these two vehicles. Also, regarding B2, even though the stress variations of 5 and 6-axle vehicles were not bigger than the TB 450, they were very close to it.

Finally, the results obtained for the bridge model 5B 0T RC 20, for beams B1, B2 and B3, respectively, are presented in Figure 14 (a), (b) and (c).





(a) (b)



(c)

Figure 14 – Stress variations found for bridges with five beams, 20 m span – 5B 0T RC 20

According to the results, it was possible to note that in B1, even though the reinforcement stress variations of the actual freight vehicles did not exceed the limit of TB 450, in 8 and 9-axle vehicles, the calculated values were closer to the respective limit.

B2 had vehicles whose stress variation were higher than the limit. The freight vehicles with 8 and 9 axles had stress variations over the calculated limit, being 9.86% and 13.55% 1.19% higher, respectively. Then, for those vehicles, TB 450 can be considered not verified. Moreover, the vehicles with 5, 6 and 7 axles had stress variations up close to the limit. Finally, in all the beams, the freight vehicles with 5, 6, 8 and 9 axles were those with higher stress variations.

4.1 Results and findings overview

This section summarizes the findings and contributions made. First, bridges and viaducts are relevant and "their absence or restricted operation by load, width or height limitations considerably reduces the level of service on the respective road segment" (Echaveguren, Dechent, 2019).

Second, the results found in this paper tie well with previous studies wherein both, this and the previous ones, have demonstrated that the longitudinal steel reinforcement of reinforced concrete beams is very susceptible to the deleterious effects of the phenomenon of fatigue. Consequently, the steel reinforcement deserves special care and attention from engineers, designers, and research, whether in the stages of design, structural recovery, so that more research and studies at the national level can be developed.

Third, according to the results, the freight vehicles with 5, 6, 8 and 9 axles were those that presented the higher stress variations in all studied beams of all bridge models, therefore, being those that tend to cause more deleterious effects compared with the others analyzed. These results lead to similar conclusions that have been found in previous studies, such as Pircher *et al*. (2011) and Rossigali et al. (2015). Moreover, if this analysis was performed, taking into consideration the data from the three toll collection points, roads with a huge volume of those vehicles deserve attention. In toll collection point 01, 5-axle is 12% of total, 6-axle is 23%, 7, 8 and 9-axle vehicles represent 14% (49% in total). In toll collection point 02, 5-axle is 13% of total, 6-axle is 18%, 7, 8 and 9-axle vehicles are 14% (41% in total).

In addition to this, although the vehicles with 2 and 3 axles did not have the highest stress variation (compared to the most critical ones), in the two collection points, they have a substantial percentual number.

In collection point 01, 2-axle and 3-axle vehicles represented 50%, in toll collection point 02, they were 42%.

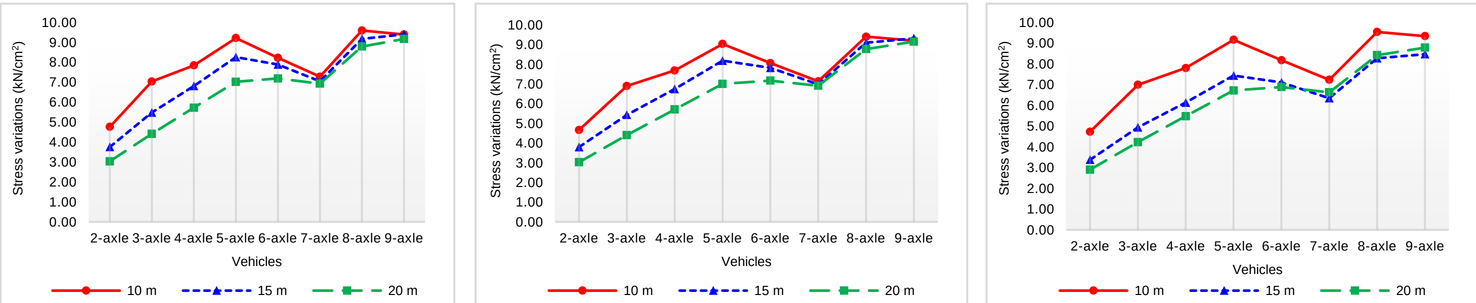
As stated before, it is not only the increase in the number of vehicles that deserves attention but also the increase in their weight is also a cause for concern. The dimensions and total weight of the vehicles of 2 to 9 axles used in this study follow the legal limits established by CONATRAN. However, freight vehicles with loads that exceed legal limits are a reality in Brazil (CNT, 2019, Fontenele, Zanuncio, Silva Júnior, 2011, Réus, Silva Júnior, Fontenele, 2014).

The previous results showed that, in some beams, although the reinforcement stress variations calculated to certain freight vehicles were smaller than their respective TB 450, they were closer to them. Then, overloaded freight vehicles are a risk, and they can cause huger stress variations than the expected ones.

Furthermore, analyzing the bridge models with three beams, the results demonstrated that in all models, beam B1 (and for consequence beam B3 because of the symmetry of the structure) was the most requested one in terms of bending moment and, consequently, of flexural stress variations in the longitudinal reinforcement. It occurred due to the position adopted to the freight vehicles that are above B1, as shown in Figure 6 (b).

Moreover, in the case of bridge models with five beams, the found results show that the beam B2 (and consequently, beam B4 due to the symmetry of the structure) presents the higher stress variations in the longitudinal stress reinforcement. It happened due to the position adopted to the freight vehicles that were above beam B2, as shown in figure 6 (c).

Based on that, using the reinforcement stress variations found in the most critical beams, Figure 15 (a) (b) (c) shows the relationship between the spans and the number of axles for bridges with two, three and five beams, respectively.



(a) (b) (c)

Figure 15 – Relationship between the spans and the number of axles for bridges

As shown by works found in the related literature, the results presented in Figure 15 explain that bridges with small spans are the ones that suffer the most from the deleterious effects of fatigue, since the values of reinforcement stress variations found for 10 m span bridges are the highest among the three models of bridges studied. Then, the biggest the stress variations, the biggest the fatigue damage.

It is essential to mention that the beams cross-section influence in fatigue resistance, so changing the cross-section of the beams may make them have bigger or smaller fatigue damage, which is directly linked with the stress variations. Secondly, the more beams the bridge has, the more efforts received by the deck are distributed to these beams; thus, the efforts on each beam tend to decrease.

Finally, it should be emphasized that this work considers only the passage of a single freight vehicle at a time in the analyzed bridge models. With this, the numerous passenger vehicles that travel are not taken into account, nor as certain traffic situations such as: more than one vehicle of the same type commuting together on the bridge, or more than one vehicle of different types traveling on the bridge, or when there is traffic on only one of the lanes, and the vehicles are stopped on the other lane of traffic on the bridge.

Those considerations are made to show that there are traffic situations that are much more complex, and they tend to generate greater demands on the structural elements of the bridges. Consequently, more significant variations in stresses will arise in the longitudinal reinforcement, which will increase the deleterious effects and damage due to fatigue.

Also, the Brazilian bridge standard has never presented guidelines or methodologies for evaluating, studying, and dimensioning existing or future bridges when data on actual freight vehicles are available.

Therefore, considering that there are traffic situations that can generate higher tensions, based on the considerations assumed here and the results presented, it is evident the need for the Brazilian bridge standard to adopt a specific train and specific coefficients for fatigue, as well as study and design methodologies when real vehicle data are available.

All those results, associated with other factors, such as the high age of Brazilian bridges and viaducts, the lack of periodic inspection and maintenance of these structures, the lack of public policies for structural conservation and recovery, as well as the lack of fatigue coefficients and live load models to fatigue are serious factors. They deserve attention because they can lead to structural problems and the rupture of these structures of paramount importance for the Brazilian infrastructure and economy.

5. Conclusions

Bridges and viaducts are elements of great importance in the infrastructure network of cities, states, and countries, especially in Brazil, which has road transport as the predominant one even more concerning road freight transportation, whose total is significant. Because of that, the increase in the number of heavy vehicles on highways and the high age of bridges and viaducts in Brazil, this work had as main objective to verify if the current Brazilian normative live load train, TB 450 was capable of representing the real freight vehicles of 2 to 9 axles concerning the fatigue process in the longitudinal reinforcement of reinforced concrete bridge beams.

The main results and conclusions found in the analyzes carried out in this work are presented below:

a) The longitudinal steel reinforcement is significantly affected by the deleterious effects of fatigue.

b) The freight vehicles with 5, 6, 8 and 9 axles are those that presented the higher stress variations in the reinforcement in the bridge models.

c) In the bridge models with two beams, beam B1 was the most critical one, and TB 450 was considered as not verified to bridge model 2B 2T RC 15 regarding the vehicle with 9 axles; and bridge model 2B 3T RC 20 regarding the vehicles with 8 and 9 axles.

d) In the bridge models with three beams, beam B1 was the most critical one, and TB 450 was considered as not verified to bridge model 3B 0T RC 15 regarding the vehicle with 9 axles; and bridge model 3B 0T RC 20 regarding the vehicles with 8 and 9 axles.

e) In the bridge models five beams, beam B2 was the most critical one, and TB 450 was considered as not verified to bridge model 5B 0T RC 15 regarding the vehicles with 8 and 9 axles; and bridge model 5B 0T RC 20 regarding the vehicles with 8 and 9 axles.

f) Although in some bridge models, the reinforcement stress variations were not hugger than their correspondent TB 450, they were very close to the limit. Taking into consideration that many vehicles travel on Brazilian highways with excess weight, this requires attention, as it can increase the active stresses on the bridge structures.

g) As the American, European and Chinese codes have both fatigue specific coefficients and load train models, it is recommended that the Brazilian code establishes its fatigue load train and coefficients, which need to be in line with the reality of Brazilian traffic and bridges. Therefore, it is recommended the development and adoption of specific methodologies, procedures, and coefficients regarding the phenomenon of fatigue to the study, design, and structural recovery of either elderly, current and forthcoming bridges and viaducts in Brazil. The adoption of such factors will allow that projects of bridges can be made more precisely, safely, and economically, and the Brazilian Bridges Code can be as robust and comparable to the best international bridge codes.

Finally, it is worth discussing these significant facts revealed by the results in terms of the Brazilian highway roads and freight vehicles. Without a doubt, the fatigue phenomenon is a current and relevant issue in the verification and design of road bridges and viaducts, and it deserves a careful investigation (experimental and/or numeric). Hence, it is highly necessary the adoption of a specific load train and specific coefficients to the fatigue phenomenon so that the analyzes of pre-existing road bridges and the design of new ones can be made most properly. So that, then, they present satisfactory structural performance over their service lives, and they are in constant consonance and adequacy with their current traffic conditions.

6. Acknowledgement

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