Safety Assessment of Concrete Bridges of the National Road Network Subject to Military Vehicle Loading

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***Abstract* - Military activities often require the use of existing structures in the national road network, namely bridges and viaducts, to meet the needs of military vehicles. These structures are designed according to the regulation at the time when the respective project was carried out, so it is important to assess whether the regulatory standards used in the design guarantee the safety of the structure for a military use.**

To this end, the different regulations of actions used in Portugal in recent decades, namely the corresponding traffic loads, were studied in order to understand the evolution of the actions considered in the design of bridge structures. In this way, it is intended to obtain the relation between the regulatory traffic and the military loads related to a mixed use.

With regard to military loading, it was considered the traffic of a tracked and wheeled vehicle, whose military load classification corresponds to the regulations approved by NATO and provided for in STANAG documents. In the scope of the evaluation of the cases of study approached, it was carried out the safety verification of the structure of the deck of three bridges inserted in the highway A1, with different structural solutions and projected according to distinct regulations.

This evaluation aims to verify the safety conditions of the deck of several bridges of the national network for a military use, both from the point of view of their resistance to the ultimate limit states and the corresponding behavior in service.

***Keywords:* concrete bridges, regulatory traffic, military load, military load classification, regulations of actions, safety assessment.**

I. Introduction

Road traffic represents the vehicles of different types that circulate on the road networks during their respective design life, namely in the operating phase of the structure and, as such, this situation constitutes an action that produces certain effects on the structure. Alongside the traffic loads, there are also other important actions that act on the structure, like its dead weight, the action of the wind, thermal effects or seismic action. Therefore, the design of a certain bridge intended for the circulation of vehicles or pedestrians must obey a set of criteria and safety requirements in order to guarantee the stability of the structure for the loads that will act during its use, as well as for actions related to accidental situations or seismic action effects.

A. Military Engineering – Concept and framework

The Armed Forces and the Army, in particular, have as their missions the permanent and unconditional support to the population, assuming a fundamental role in guaranteeing defense, security and independence of the national territory. To this end, the military organization is subdivided into several areas, in order to perform their respective functions with the best possible quality and accuracy. Military Engineering refers to the Portuguese Army's specialty that is associated with the fulfillment of specific missions in the field of mobility, counter mobility and protection, whose valences are intended to support the combat forces in times of war, as well as assisting the population and civil entities in periods of peace. Thus, Engineering is present in the most diverse military operations associated to offensive and defensive operations, in which it integrates the front line due to its operational diversity and its essential competences to the fulfillment of military duties.

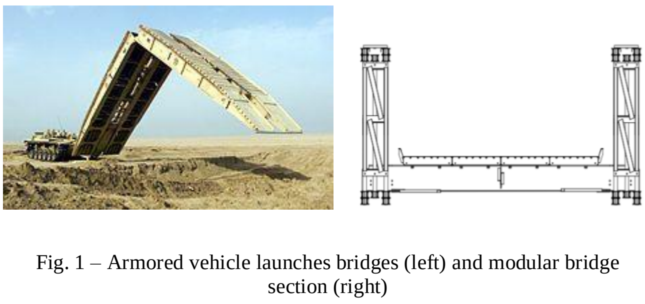

Fig. 1 – Armored vehicle launches bridges (left) and modular bridge section (right)

Between 1961 and 1974, during the colonial war, Military Engineering played an important role in the events of the theater of operations in Africa, of which the actions of social modernization, the creation of essential infrastructures, the implementation and improvement of communication and transport networks and the support to industrialization stand out. Between the end of the African conflict and 1995, the activities of Military Engineering corresponded mainly to missions in support of the population and various actions in the field of civil protection, in partnership with civil entities and with presence throughout the national territory. Since then, the Military Engineering activities have been essentially focused on the integration in detached national forces in the international cooperation framework, in order to provide support in peacekeeping or peace enforcement operations. [10] The following modules are part of the Military Engineering competency framework:

- Emergency constructions;
- Engineering equipment;
- Sappers;
- Bridges;
- Water collection and purification.

B. *Military bridges*

Regarding the transposition of obstacles, the military forces are equipped with specific means and adequate technical knowledge in order to overcome obstacles such as valleys or watercourses. Thus, the means of transposition used by the Army are subdivided into two distinct characteristics, namely:

- Discontinuous:
    - Floats;
    - Boats;
    - Flybridges.
- Continuous:
    - Footbridges;
    - Bridges.

In general, the use of discontinuous means of transposition refers to situations related to offensive operations, due to their lower weight and lower load capacity, compared to continuous means. These, heavier, allow a greater load capacity and are more complex in terms of their assembly and operability. They are usually used at the rear of the armed conflict front. However, both are considered provisional structures due to their temporary character in relation to the expected period of use.

Fig. 2 – Floating bridge (left) and Mabey & Johnson military bridge (dir.)

C. *STANAG 2021 – Military Load Classification (MLC)*

The NATO regulations concerning the MLC system consider 32 hypothetical vehicles, which are divided in wheeled and tracked vehicles, in which the various configurations of the former in relation to the number of wheels and their axles are highlighted. Thus, the military vehicles are characterized by 32 classes, namely between MLC 4 and MLC 150. Regarding the classification of bridges, additional characteristics are defined as the height of the center of gravity, area of side wind and height of the center of pressure. It should be noted that the MLC system is only a form of classification associated to military vehicles, this value does not correspond to the mass of the same with respect to wheeled vehicles, because in this situation are considered aspects such as maximum axle load, contact width of the tire and axle spacing. In order to classify a military vehicle, it is necessary to calculate the maximum forces it produces in relation to the various span lengths associated with a simply supported configuration, in order to plot the curves associated with the MLC system.

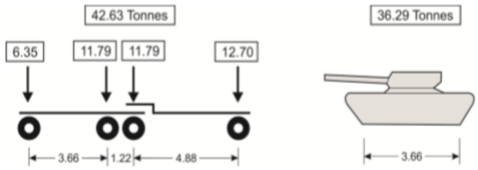

Fig. 3 – MLC 40 wheeled reference vehicle (left) and MLC 40 tracked reference vehicle (right)

In campaign or in emergency situations, the expeditious classification of a vehicle can be achieved by considering the mass equivalent to its total load, the value of which is found in the manufacturer's indications or in the operation manual. In this way a temporary and expedited military load classification is obtained. This method integrates a safety margin corresponding to the multiplication of the value of the total mass by a factor corresponding to 1,20 or 1,10 for tracked or wheeled vehicles, respectively. [4] The MLC system used in the characterization of bridges aims to ensure safe circulation by all military vehicles, serving as a methodology and guidance for the realization of military classification. Therefore, it should be noted that the parameters and indications associated to this classification system are not intended for instructions concerning the design of bridges. Three different traffic conditions are considered, being that only the last two represent an increase over the military class of the bridge:

- Regular traffic: allows the use of the bridge without restrictions by military vehicles whose MLC numbering is equal to or less than the maximum allowed value, and only this classification can be assigned permanently.
- Caution traffic: maintains the same level of safety as the normal traffic, although with the following restrictions:
    - maximum speed limit of 5 km/h;
    - conditioning of accelerations, braking and speed changes;
    - circulation restricted to the center line of the carriageway;
    - circulation of only one vehicle in each span structurally independent.
- Risk traffic: conditions of circulation equal to the caution traffic, being additionally reduced the respective safety margin and admitting permanent damage to the structure. [4]

It is highlighted the exclusive consideration of the type vehicle, according to the MLC system, in the scope of the variable actions in the structure, not being included, therefore, the contribution of any distributed load simultaneously with the action relative to the loading of the correspondent type vehicle. [15] In general, the following partial safety coefficients can be assumed for the overall evaluation of most bridges, the variable load being that of military vehicles, and the definition of which is based on the MLC system. [4]

Tab. 1 – Safety coefficients proposed by STANAG 2021 [4]

Traffic conditions	**Safety coefficient (γ)**	
	Permanent load	***Variable load (MLC)***
Regular	1,20	1,35
Caution	1,20	1,22
Risk	1,17	1,17

The reliability index β translates into the degree of confidence corresponding to the expected behavior of a given structure, the safety margin being obtained through the difference between the values of resistance and actual load acting. Thus, the probability of collapse of the structure P_c is inversely related to the above mentioned index, as exemplified in the following table:

Tab. 2 – Relation between the reliability index and the probability of collapse of a structure [5]

P_c	0,5	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
β	0	1,28	2,32	3,09	3,72	4,27	4,75	5,20

STANAG 2021 considers an adjustment to the coefficients that affect the load applied by the reference vehicle corresponding to the respective military class, as well as the permanent load associated to the structure's dead weight. The premises supporting these changes concern in a more realistic and precise definition by the military model regarding the characteristics of the reference vehicle, as well as an increase in the level of risk associated with the use of the structure. Thus, the safety coefficients adopted by the military regulations result from a reduction in the degree of uncertainty regarding the variables considered in the safety check. The safety coefficients related to NATO standards are based on lower reliability index, corresponding to 3,3 for normal and caution crossing conditions, and for risk situations it varies between 2,4 and 2,9 according to the reference period adopted.

II. Evolution of Action Regulations

The following rules represent the development of regulations associated with the design of bridge structures, with a view to understanding and analyzing their evolution.

A. Regulamento para Projeto, Provas e Vigilância das Pontes Metálicas (1897)

For road bridges, a uniform load corresponding to 400 kgf/m^2 should be considered, applied on the sidewalks and on the lanes of the road platform not occupied by vehicles, as well as a uniform load with a width equal to 2,50 meters, whose value varies according to the following table:

Tab. 3 – Uniform load, variable with the bridge span [16]

Span [m]	**4**	**6**	**8**	**10**	**15**	**20**	**30**
UDL* [kgf/m^2]	3000	2050	1650	1550	1350	1100	1000

* Uniformly distributed load

For spans over 30 meters, only the uniform load 400 kgf/m^2 referred to in the previous paragraph applies. Regarding the calculation of the linear elements, the load scenario is associated to the loading of a reference vehicle, with two axles spaced 2,0 meters and a weight of 6,0 tons per axle, as well as a width corresponding to 1,60 meters.

B. Regulamento de Pontes Metálicas (1929)

As far as road bridges are concerned, a load must be applied to the carriageway with the characteristics presented in the figure below, the axle width being equal to 1,50 meters and the total width of each vehicle corresponding to 2,50 meters. The loading of the reference vehicle is applied simultaneously in all lanes, whose location corresponds to the most conditioning scenario in relation to the forces produced, being also applied a load on the sidewalks corresponding to 400 kgf/m^2.

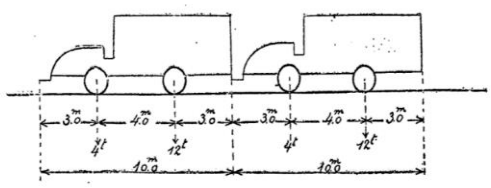

Fig. 4 – Reference vehicle loading applied on the carriageway [20]

The type of load referred to above is used in the design of linear elements of bridges with reduced spans. Regarding the calculation of main beams with spans equal to or greater than 80 meters, the regulation adopts a uniform load with a minimum value of 500 kgf/m^2, instead of the previous one, defined by the following expression:

$$q = 820 - 4l_{span}\ [kgf/m^2] \quad [1]$$

Regarding the dynamic coefficient for road bridges, it should be applied in the calculation of the carriageway loading, being its value obtained through the following formula:

$$\varphi = 1{,}0 + \frac{60}{l_{span} + 150} \quad [2]$$

C. Regulamento de Pontes Metálicas (1958)

The present publication serves to enact a new wording of Article 43 of the Metallic Bridges Regulation (1929), whose amendment concerns the scope of the loads adopted in the design. Two types of traffic loads are fixed regarding the calculation of the main structure and of the deck elements, namely a reference vehicle and a uniform load. Regarding the reference vehicle, its definition is related to the respective load class, and the corresponding loads must be affected by the dynamic coefficient. The following figure demonstrates the characteristics associated to the reference vehicle:

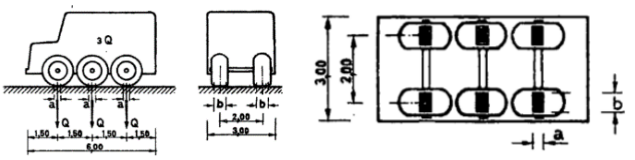

Fig. 5 – Arrangement and dimensions of the reference vehicle [17]

Tab. 4 – Characteristics of the reference vehicle according to the corresponding class [16]

Class	Q [t]	a [m]	b [m]
A	20	0,35	0,60
B	15	0,32	0,50
C	10	0,28	0,40

It is considered a uniform distributed load on the deck surface, simultaneously with a uniformly distributed linear load in the transverse direction of the carriageway. This situation translates into a load of 400 kgf/m^2 applied on the sidewalks and on the carriageway as well as a linear load of 5 tf/m applied transversally to the track, not being these loads affected by the dynamic coefficient and located in the area of the deck that produces the most conditioning effects for the element under study.

D. Regulamento de Solicitações em Edifícios e Pontes (1961)

Regarding the design of road bridges, two different loads are considered, taking for the project the one that produces the most unfavorable effects. One of the previous is applied to the carriageway and consists in the reference vehicle represented in Fig. 5, in which its position corresponds to the location associated with the greatest forces. It should be noted that the load in question must be affected by a coefficient corresponding to 1,2 in order to take into account the dynamic effects. Regarding the distributed load, this constitutes a uniform load of 300 kgf/m^2 applied on the carriageway and on the sidewalks, and a linear load, with a value corresponding to 5 tf/m and applied only on the carriageway and on a single section of the deck, not being affected by the dynamic coefficient.

E. Regulamento de Segurança e Ações para Estruturas de Edifícios e Pontes (1983)

Regarding specific actions on bridges, two types of loads on the carriageway are considered separately, the first being a reference vehicle with three equidistant axes and the second a load consisting of a uniformly distributed load, q_1, and a transversal load with linear and uniform distribution, q_2. The layout and dimensions of the reference vehicle are shown below, as well as the values for the distributed loads, according to the class of the bridge.

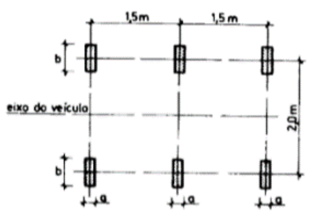

Fig. 6 – Arrangement and dimensions of the reference vehicle [18]

Tab. 5 – Characteristic values of the loads and dimensions of the wheelsets of the reference vehicle [18]

Class	a [m]	b [m]	*Q* [KN]	q_1 [KN/m^2]	q_2 [KN/m]
I	0,20	0,60	200	4	50
II	0,20	0,40	100	3	30

F. Eurocode 1 – Actions on structures, Part 2: Actions on bridges traffic

The documents related to the Eurocode are presented as the most recent regulation concerning the design of structures, being a European standard whose implementation has been adopted by most of the European Union countries. Regarding the load models, the load model 1 (LM1) whose use concerns the effects of truck and car traffic, which is considered in global and local checks, should be noted. The LM1 foresees situations of fluid or congested traffic, associated with a composition corresponding to a high percentage of heavy vehicles, which consists of two partial systems, namely concentrated loads associated with a double axle type vehicle (TS) and uniformly distributed loads (UDL). The characteristic values corresponding to Q_k and q_k, including the effects of dynamic amplification, are represented in the table below, according to the numbering of the lane and the type of load:

Tab. 6 – Characteristic values related to EC1-2 (LM1) [19]

Location	TS	UDL
	Q_k (axle load) *[KN]*	q_k *[KN/m^2]*
Lane 1	300	9,0
Lane 2	200	2,50
Lane 3	100	2,50
Other	0	2,50
Remaining area	0	2,50

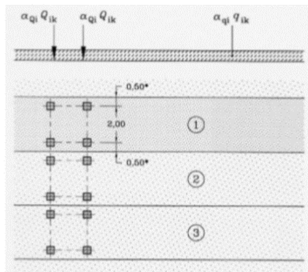

Fig. 7 – Graphic representation of the LM1 application [19]

III. Global Analysis – Preliminary Approach

In order to take into account the evolution of regulations concerning traffic loads, a simplified analysis of the effects produced by the different actions associated to the regulations used in bridge structure projects over the last decades was carried out. Since the various regulations consider different traffic loads, the comparative analysis is performed for a certain lane width. Thus, a carriageway consisting of two 3,5-meter-lane and two 1,0-meter-border is considered, resulting in a total width corresponding to 9,0 meters. The comparison will be made in terms of the global forces acting on different span lengths. The global forces considered relates to the total bending moment, being thus the so-called global effects of loads. This simple approach allows, in a first analysis, to verify if there are deficiencies in terms of the resistance of the deck of bridges designed according to the different regulations. In this analysis the local effects in which the conditioning load corresponds to the effect of the reference vehicle are not considered. For the circulation of military vehicles, it is considered the load associated with tracked vehicles of class 70 (63,5 t) and wheeled vehicles of class 100 (104,3 t), according to the military load classification provided for in NATO regulations, as shown below:

Fig. 8 – Leopard 2 A6 (left) and heavy transport vehicle (right) [Defense Forum]

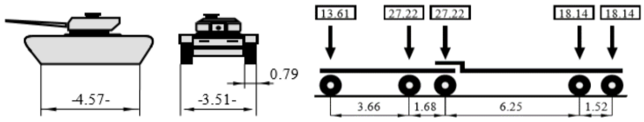

Fig. 9 – Characteristics of the tracked and wheeled type vehicles [STANAG]

A lane reserved for the exclusive circulation of military vehicles is defined, the remaining area being subject to the traffic loading of Eurocode 1, namely reference vehicle 2 (400 KN) and reference vehicle 3 (200 KN), as well as the action of the correspondent uniform load. The loading situation in question is defined in the table below:

Tab. 7 – Loading situation for the circulation of military vehicles with reserved track

	Axle load [KN]	Uniform load [KN/m^2]
Lane 1 (military traffic)	Fig. 9	0
Lane 2 (normal traffic)	200	2,50
Lane 3 (normal traffic)	100	2,50

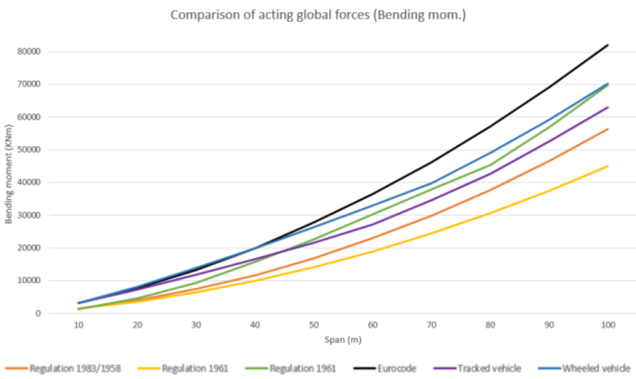

Fig. 10 – Comparison of global forces acting according to various regulations

Assuming that a current situation of military circulation presents normal crossing conditions, the reliability index β associated to this scenario corresponds to 3,3, as foreseen by STANAG 2021. Considering that the uncertainty associated with the military vehicles' load model is quite low (7%), a partial coefficient γ_Q of 1,35 is obtained.

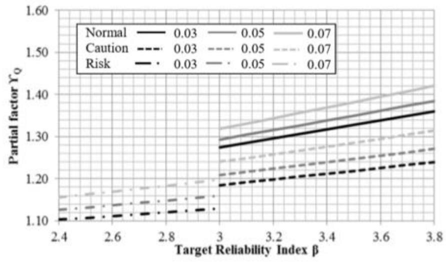

Fig. 11 – Partial safety coefficient for variable actions according to different crossing conditions and for an uncertainty of the loading model between 3% and 7% [15]

Affecting the military load and the regulatory loads of partial safety coefficients corresponding to 1,35 and 1,50 respectively, it can be obtained the total bending moment associated to the considered loads.

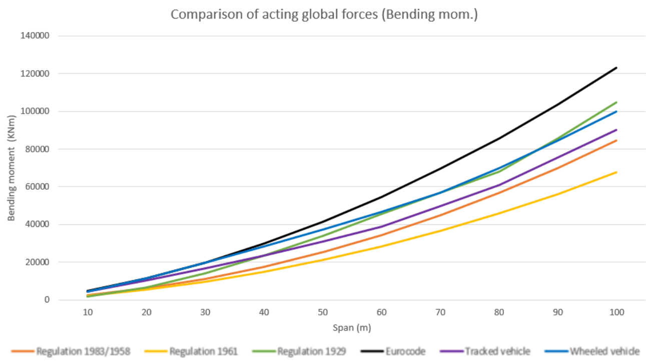

Fig. 12 – Comparison of the global active forces affected by the safety coefficient according to various regulations

Thus, it is concluded that:

- For short span lengths of less than 40 meters, the loading scenario relative to the circulation of military vehicles is more unfavorable when compared to the different regulations, and the effects produced by the wheeled type vehicle are relatively similar to the traffic loads considered in the Eurocode;
- For intermediate spans, between 40 and 80 meters, the traffic model associated to the wheeled and tracked military vehicles results in slightly higher forces than those relative to the 1929 Regulation and the 1983 Regulation, respectively, and the military load presents more unfavorable forces compared to the regulatory traffic load relative to the 1961 Regulation;
- For high span lengths, over 80 meters, the traffic loads of the 1929 Regulation result in identical forces compared to those of the wheeled military vehicles, and the tracked vehicle scenario presents an acting force higher than the loading foreseen by the 1983 Regulation.

IV. Case Studies – Checking the Safety of the Deck

In this chapter it is verified the safety of the deck of three bridges with different structural solutions, designed according to the old regulations.

A. *Alhandra viaduct*

In this evaluation, the safety check is carried out in relation to the Ultimate and Service Limit States of the structure of the deck referring to the present viaduct.

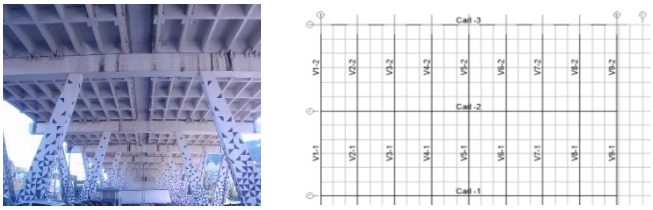

Fig. 13 – Alhandra viaduct (left) and structure elements analysed (right)

The analysis of the effect of the different traffic loads on the structure elements was carried out considering the forces on the beams for the characteristic combination. Thus, it is interesting to obtain the forces in the main structural elements for the real loads relative to the traffic models considered. The objective of this analysis is to verify if the military traffic causes damage to the deck beams, so the values of the loads are considered without any reduction associated.

$$\sum_{j\geq 1} G_{k,j} + G_{k,1} + \sum_{i>1} \psi_{0,i} Q_{k,i} \qquad [3]$$

The table below shows the maximum force involved in the characteristic combination of actions. (Note: on the longitudinal beams the most adverse combination concerns the uniform load).

Tab. 8 – Maximum bending moment on longitudinal beams

	Bending moment [KNm]					
	1929 Regulation		1958 Regulation		Military load	
	$M_{span}^{1/2}$	$M_{span}^{1/4}$	$M_{span}^{1/2}$	$M_{span}^{1/4}$	$M_{span}^{1/2}$	$M_{span}^{1/4}$
B1-8	745,0	572,0	779,2	598,5	1085,2	809,8
B9	738,5	565,7	714,4	543,5	714,0	535,9

Tab. 9 – Determination of the bending moments that lead to the decompression of the control sections

		A [m²]	W$_{bot}$ [m³]	P [KN]	M$_{decompression}$ [KNm]
½ span	**B1-8**	0,377	0,446	1026$^{(a)}$	1159
	B9	0,307	0,0421	1173$^{(b)}$	1171
¼ span	**B1-8**	0,377	0,446	1026	1038
	B9	0,307	0,0421	1173	1043

(a) 2 8-wire and 1 12-wire cable; (b) 1 12-wire and 2 8-wire cable

It is concluded that, in general, the loads associated to the military traffic considered produce higher forces in the longitudinal beams compared to the traffic loads of the 1929 and 1958 Regulations, and in relation to the inner beam (B9) the forces are practically identical for the loading cases considered. The loads corresponding to the characteristic combination of actions do not induce tensile stresses in the longitudinal beams, so it is considered that no damage occurs in the structural elements referred to for the service loads.

The following figure shows the deformation on the deck for different actions.

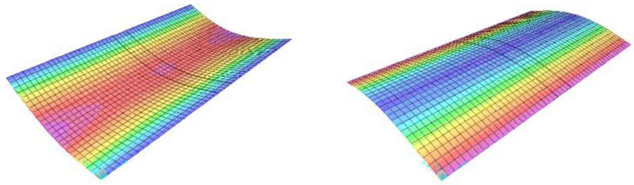

Fig. 14 – Deformation of the deck due to permanent loads (left) and effect of prestressing action (right)

The combination of actions regarding the present structural verification concerns the fundamental combination of actions, being that in the safety verification relative to the Ultimate Limit State the structure of the deck was evaluated for the critical sections, in order to evaluate the resistance of the previous ones to bending and shear forces.

$$F_d = \sum_{j=1}^{m} \gamma_{gj} F_{G_{j,k}} + \gamma_q \left(F_{Q_{1,k}} + \sum_{j=2}^{n} \psi_{0j} F_{Q_{j,k}} \right) \qquad [4]$$

Being that:

- γ_{gj}=1,35 (permanent loads)
- γ_q=1,5 (variable loads)

It should be noted that, according to the regulations approved by NATO, the partial coefficients for safety checks involving the circulation of military vehicles correspond to 1,2 and 1,35 for permanent and variable loads, respectively.

Tab. 10 – Maximum forces on longitudinal beams for the fundamental combination of actions

	Military loading			
	Bending moment [KNm]		Shear force [KN]	
	$M_{Sd,\ 1/2\ span}$	$M_{Sd,\ 1/4\ span}$	$V_{Sd,\ support}$	$V_{Sd,\ 1/4\ span}$
B1-8	1398,6	1045,2	346,3	211,8
B9	904,4	677,6	209,9	118,7

The values of the resistant moments relative to the control sections of the deck are found in the following table, considering only the interior prestress. The increase of the resistant moment related to the strengthening of the beams with external prestress is presented in expression 5.

Tab. 11 – Resistant bending moment in the control sections of the longitudinal beams

	Resistant bending moment [KNm]	
	$M_{Rd,\ 1/2\ span}$	$M_{Rd,\ 1/4\ span}$
B1-8	1219	1060
B9	1340	1135

$$M_P = F_P \times e = 500 \times 0{,}72 = 360\ KNm$$
$$=> M_{Rd,total} = 1219 + 360 = 1579\ KNm \qquad [5]$$

It is verified that the safety check is satisfied if the increased resistance associated to the effect of the external prestress is considered. The safety check in relation to the resistance of the control sections to shear was performed having been considered the prestressing on the action side.

$$V_{Rd} \geq V_{Sd} - P \times \tan\alpha \qquad [6]$$

$$\frac{A_{sw}}{s} = \frac{V_{Sd} - P \times \tan\alpha}{0{,}9 \times d \times cotg\theta \times f_{yd}} \qquad [7]$$

Knowing that the longitudinal beams have a shear reinforcement Ø3/8"//0,20 and that the area of a rod Ø3/8" is equal to 0,71 cm^2, it results that the shear reinforcement corresponds to 7,1 cm^2/m. Therefore, the value of the shear resistance V_{Rd} corresponds to 247,7 KN.

Tab. 12 – Verification of the shear reinforcement in the longitudinal beams

		$P \times \tan\alpha$	V_{Sd} [KN]	$V_{Sd} - P \times \tan\alpha$
Beams 1-8	**Support**	117,8	346,8	229,0
	¼ span	67,3	211,3	144,0
Beams 9	**Support**	124,2	244,0	119,8
	¼ span	70,8	150,1	79,3

It is therefore concluded that the longitudinal beams verify the safety with respect to the Ultimate Limit State of shear.

B. Viaduct over the Trancão river

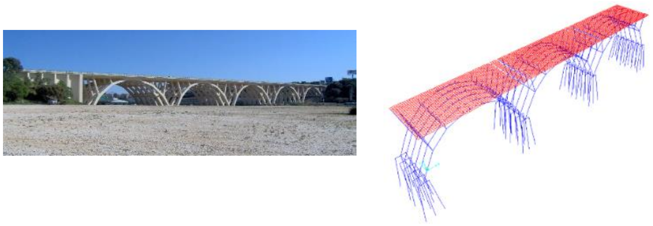

Fig. 15 – Viaduct over the Trancão river (left) and global model (right)

In the analysis of forces on the slab, it is considered the vehicles type associated to regulatory traffic and military loading, whose local effect is considered conditioning for the intended evaluation.

Tab. 13 – Slab design bending moments in longitudinal (*x*) and transversal (*y*) directions

	Slab design bending moments [KNm/m] – TS		
	1929 Regulation	*1958 Regulation*	*Military loading*
$m_{x,max}$	15,9	18,2	15,7
$m_{y,max}$	17,0	28,8	33,4
$m_{y,min}$	-30,5	-82,8	-88,3

Considering for steel class S235 and for structural concrete class C30/37, as well as a slab thickness corresponding to 0,20 m and 0,40 m in the span and in the support area, respectively, the following resistant moments result:

- Longitudinal direction: $m_{x,Rd}$ = 26 KNm/m;
- Transversal direction: $m_{y,Rd}$ (positive) = 46 KNm/m;
- Transversal direction: $m_{y,Rd}$ (negative) = -101 KNm/m.

Comparing the maximum slab bending moments with the resistant moments it is concluded that the local effects relative to the military traffic verify the safety for bending forces. Regarding the shear acting on the slab in the support area, the following values were obtained on the beams:

Tab. 14 - Shear on the slab next to the support section

	Permanent load [KN]	Overload [KN]	V_{Sd} [KN]
1929 Regulation	16,9	44,5	89,6
1958 Regulation	16,9	68,8	125,6
Military traffic	16,9	94,5	147,9

$$V_{Rd,c} = \left[\frac{0{,}18}{1{,}5} \times \left(1 + \sqrt{\frac{200}{375}}\right) \times (100 \times 0{,}02 \times 30)^{\frac{1}{3}}\right] \times 1000 \times 375 \times 10^{-3} = 270{,}1\ KN \qquad [8]$$

$$V_{Rd,c} \geq \left(0{,}035 \times \left(1 + \sqrt{\frac{200}{375}}\right)^{\frac{3}{2}} \times 30^{\frac{1}{2}}\right) \times 1000 \times 375 \times 10^{-3} = 163{,}6\ KN \qquad [9]$$

Thus, it is concluded that the slab does not present any problems in relation to shear, verifying the safety with a considerable margin.

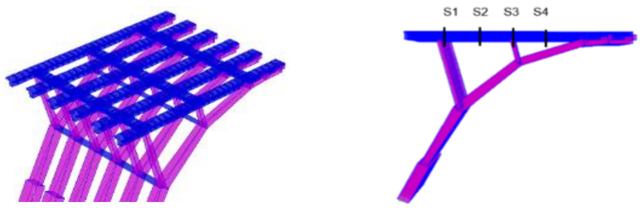

Fig. 16 – 3D view of the control sections: support of the beams in the connection to the corresponding supports and half span sections

Tab. 15 – Transversal arrangement of the load relative to the military traffic

	Carriageway 1			Carriageway 2		
Lane number	**1[1]**	**2**	**3**	**1[2]**	**2**	**3**
TS (total load) [KN]	635	400	200	400	200	0
UDL [KNm]	0	2,50	2,50	2,50	2,50	2,50

[1] End lane; [2] Inner lane.

Tab. 16 – Maximum bending forces in the longitudinal beams for the fundamental combination of actions

		Beams – Bending moment [KNm]			
Control sections		**1**	**2**	**3**	**4**
Regulation 1929	**UDL**	-896,8	1610,4	-1087,4	2080,4
	TS	-561,0	1201,2	-779,6	1322,6
Regulation 1958	**UDL**	-715,4	1516,9	-910,9	1791,6
	TS	-674,9	1771,5	-887,0	1777,5
Military load		-731,3	1943,5	-939,8	2091,5

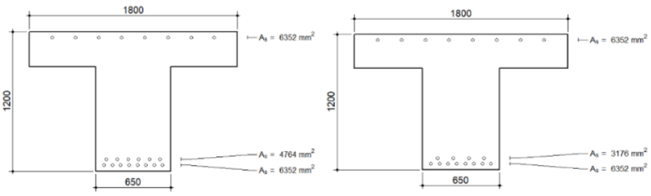

Fig. 17 – Reinforcement in span sections: section 2 (left) and section 4 (right)

Tab. 17 – Resistance to bending of linear structural elements in the support and half span sections

	Resistant bending moment [KNm]
Section 1	-2118
Section 2	2503
Section 3	-2766
Section 4	2184

It is verified that the elements analyzed verify the safety relative to bending forces.

C. Viaduct over the Mouros river

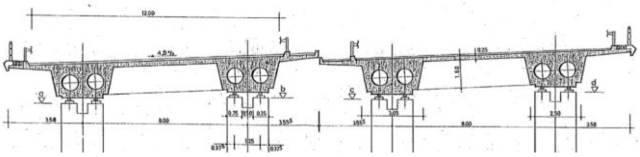

Fig. 18 – Design drawing of the ribbed slab deck structure (cross section)

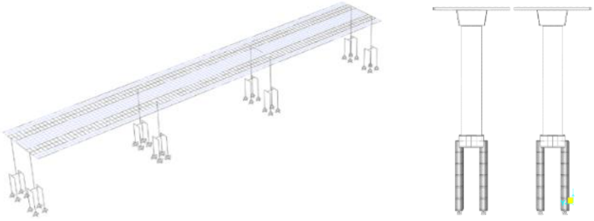

Fig. 19 – 3D view of the central panels and detail of a cross section

In order to obtain the forces in the deck for the action of the loads under analysis, several loading arrangements were considered in relation to the support sections and the half-span. Considering the hyperstatic moment associated to the effect of the slab prestressing in the support area, it comes that:

$$M_P^{slab} = 1362,4\ KNm;\ M_P^{rib} = 7960,7\ KNm \qquad [10]$$

Where,

$$M_P^{total} = 9323,1\ KNm \qquad [11]$$

Thus,

$$\begin{aligned} M_{iso} &= P \times e \\ &= 10000 \times (0,643 - 0,12) + \frac{7000}{2} \times (0,643 - 0,125) \\ &= 7043\ KNm \end{aligned} \qquad [12]$$

$$M_{hip} = M_P - M_{iso} = 9323,1 - 7043 = 2280,1\ KNm \qquad [13]$$

The bending forces in the half-span sections and in the support of the central panel of the deck for the characteristic and fundamental combinations of actions are presented below, in order to verify the safety of the structure for the service loads and for the Ultimate Limit State, respectively.

Tab. 18 – Bending forces in the support and the mid-span of the central panel of the deck

		Bending moment [KNm]		
		1983 Regulation (TS)	***1983 Regulation (UDL)***	***Military load***
Characteristic combination	**½ span**	11692,6	13780,4	19353,2
	Support	-13019,1	-16232	-17243,6
Fundamental combination	**½ span**	15311,5	18443,1	24241,5
	Support	-18395,3	-23214,6	-21803,5

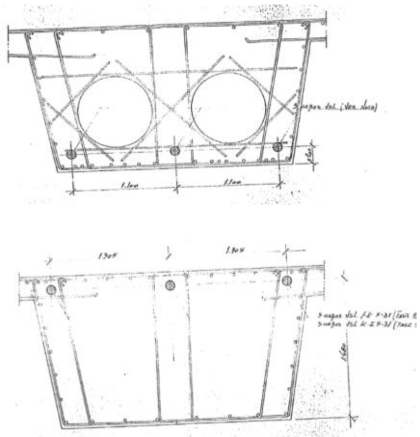

Fig. 20 – Designs drawings (longitudinal prestressing): half span section (top) and support section (bottom)

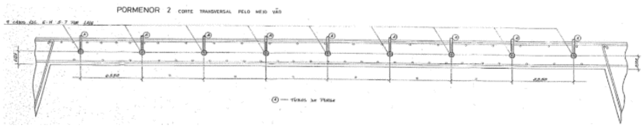

Fig. 21 – Longitudinal prestressing of the slab between ribs (cross section)

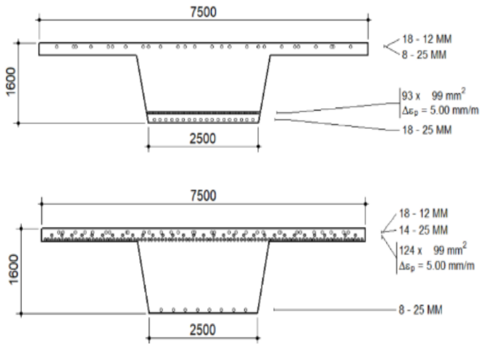

Fig. 22 – Modeling of the middle span section (top) and support section (bottom)

This results in the following values for the resistant bending moment:

- Mid-span section: M_{Rd} = 22772 KNm;
- Support section: M_{Rd} = -25648 KNm.

It is verified that in the support section the resistant bending moment is higher than the actuating moment and in the middle section the bending force is higher than the respective resistant capacity, so it is concluded that the deck structure does not verify the safety relative to the Ultimate Limit State. The following table shows the values for the shear relative to the traffic loads considered:

Tab. 19 – Maximum and minimum values of the shear in the support section of the central panel of the deck

		Shear force [KN]		
		1983 Regulation (TS)	***1983 Regulation (UDL)***	***Military load***
Fundamental combination	**V_{min}**	-3654,2	-4085,9	-4985,8
	V_{max}	3585,8	4170,0	4467,6

The safety check to the Ultimate Limit State is calculated according to the existing shear reinforcement and considering the prestressing on the action side.

$$V_{Rd} = \frac{A_{sw}}{s} \times 0{,}9 \times d \times cotg\theta \times f_{yd}$$
$$= 27{,}16 \times 10^{-4} \times 0{,}9 \times 1{,}55 \times 2 \times 348 \times 10^{3} \quad [14]$$
$$= 2637\ KN$$

$$V_{Rd} \geq V_{Sd} - P \times \tan\alpha \quad [15]$$

Tab. 20 – Checking the shear reinforcement in the support section

	F_P^{rib}	$tg\ \alpha = \frac{4f}{L}$	$P.tg\ \alpha$	V_{Sd}^{max}	$V_{Sd} - P.tg\ \alpha$
Support [KN]	10000	0,364	3640	4985,8	1345,8

It can be concluded that the safety relative to shear is verified considering only the effect of the prestressing applied to the rib. Assuming an average tensile strength f_{ctm} corresponding to 2,6 MPa (C30), the upper and lower fiber stress is calculated for the characteristic combination relative to military loading.

$$\sigma_{top} = -\frac{10000 + 3500}{5{,}62} - \frac{10000 \times 0{,}523 + 3500 \times 0{,}518}{2{,}07} + \frac{17243{,}6}{2{,}07} = 2{,}53\ MPa \quad [16]$$

$$\sigma_{bot} = -\frac{10000}{5{,}62} - \frac{10000 \times 0{,}757}{1{,}39} + \frac{19353{,}2}{1{,}39} = 6{,}70\ MPa \quad [17]$$

In this way, it is admitted the occurrence of damages in the structure for the service loads considered. The tension in the ordinary reinforcement and in the prestressing reinforcement is then determined for the military traffic corresponding to the service loads.

Tab. 21 – Ordinary and prestressed reinforcement tension for loads relative to the rare combination of actions

	M_{rare} $[KNm]$	σ_s $[MPa]$	σ_s^P $[MPa]$
Support	-17243,6	175,2	1148,7
½ span	19353,2	322,4	1277,2

It can be seen that for the negative moment the reinforcement presents moderate values of tension compared to the corresponding load, and for positive moments the level of tension in the ordinary reinforcement presents significant values, so that it is expected relevant cracking in relation to the military load considered.

V. CONCLUSIONS

One of the objectives of this dissertation concerns the understanding of the different regulations used in Portugal in the last decades, namely the consideration of the respective traffic loads in the design of bridge structures. It was also studied the relationship between the regulatory traffic loads associated to different regulations and the military loads related to a mixed use referring to normal traffic simultaneously with military circulation. Thus, it was intended to evaluate the safety conditions of the deck structure of viaducts with different span lengths and whose design concerns different action regulations, in order to verify whether the loads used in the project guarantee the safety of the structure for a military use, both from the point of view of resistance to the ultimate limit states and the corresponding behavior in service.

In a first analysis it was studied the relationship between the various regulations in relation to a bar model, in order to obtain a comparison of the overall forces for variable span lengths. Regarding military traffic, class 70 and class 100 were considered in relation to the loading associated to the tracked and wheeled vehicle, respectively, the first corresponding to a Leopard 2 A6 armoured vehicle and the second associated to a heavy transport vehicle loaded at its maximum capacity.

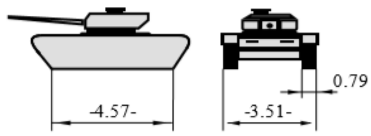

Fig. 23 – Tracked reference vehicle (MLC 70) [STANAG]

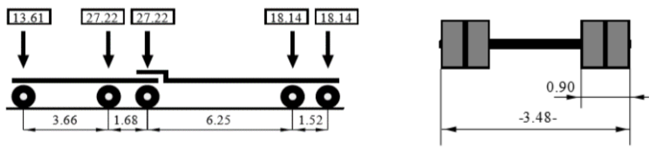

Fig. 24 – Wheeled reference vehicle (MLC 100) [STANAG]

In order to validate the conclusions obtained for the overall analysis, which are appropriate for most bridge structures due to the simplicity of the studied bar model and the variation of its span length, an evaluation was made of three constructions inserted in the A1 highway, in which the correspondent design date from different periods and, consequently, these are based on regulations of equally distinct actions. Thus, the case studies analyzed concern the following structures:

- Viaduct over the Trancão river (Sacavém, 1959): reinforced concrete deck;
- Alhandra Viaduct (Vila Franca de Xira, 1960): reinforced concrete prestressed deck;
- Viaduct over the Mouros river (sublance Pombal-Condeixa, 1990): prestressed reinforced concrete deck.

Thus, considering the overall analysis carried out and based on the results obtained in the safety evaluation of the case studies addressed, it can be seen that the bridges whose design is related to the old regulations, namely the Metallic Bridges Regulation (1929), have a lower tendency to give rise to structural safety problems when subjected to military loads. On the other hand, due to the adoption of less unfavorable loads compared to previous regulations, structures designed according to most recent regulations, such as the 1983 Regulation, present a greater tendency to originate safety problems when compared to military use.

For bridges with a span length of small to medium, up to about 30 to 40 meters, it is concluded that the various regulatory loads lead to relatively similar forces, with military traffic inducing greater forces on the structure than the previous. For spans longer than 40 meters, the loads associated to the circulation of the military tracked and wheeled vehicles considered, namely class 70 and class 100, lead to slightly higher forces compared to the traffic loads of the 1983 and 1929 Regulations, respectively. As such, in situations for which it is foreseeable that, through information related to the class of military vehicles in question and the characteristics of the bridge they intend to cross, the active forces related to military loading will be identical or superior to the loads used in the design of the structure, military traffic must be conditioned or reserved in order to avoid the risk of collapse of the structure or the occurrence of permanent damage. In these situations, the circulation of military vehicles should be carried out at a moderate speed, in the center of the carriageway, with only one vehicle in each span structurally independent, and the remaining road traffic should be temporarily conditioned.

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