Influence of design techniques on load distribution and bearing capacity of existing bridges

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Summary

The evaluation of existing concrete structures must consider the actual structural properties and the key design principles commonly used. For bridges, the design principles may significantly influence the structural behavior, as in past decades, load distribution was based on simplified 2D representations that did not accurately represent the 3D load effects. This study analyses how the design tools used in past decades may influence the load distribution and the design stresses for four bridges. Generally, 2D stress distribution methods tend to overestimate the live loads, increasing the combined stresses. Consequently, this results in reinforcement overestimation and the enhancement of the bridge load-bearing capacity. Thus, bridges constructed in past decades have an inherent hidden capacity due to the conservatism of past design tools, which may help understand their ability to sustain current live loads.

1 INTRODUCTION

Bridges are important structures for a country's socioeconomic system, as they connect people and enable the transport of goods and services. Such structures become especially important in a country like Brazil, where road transport is the predominant mode of transport [1].

The aging of the bridges is a global problem. In the United States, 45% of bridges have been in service for over 50 years [2]. In Japan, this number was 27% in March 2019 and will be 52% in March 2029 [3]. In Brazil, 27% of the bridges are older than 50, while 41.3% have an unknown age [4].

In parallel with the aging of structures, over the years, there have been major developments in the regulatory criteria for designing structures and the materials' properties [5]. In addition, there has also been a considerable increase in the load capacity of vehicles travelling on the roads. In other words, as structures have deteriorated, the stresses to which they are subjected have increased.

According to Guimarães et al. [6], changes in the design characteristics of reinforced concrete bridges (changes in loads and cross-sections) have required revisions of the Brazilian Standards for the design and execution of these structures. The codes for the design of bridges in Brazil have changed considerably in past decades, the main change being the switch from the Allowable Stress Method to the Limit State Method [7].

This scenario requires the assessment of the in-service bridges to ensure their safety. The analysis of existing structures must consider the original conditions under which they were designed, i.e. the standards and tools available. These conditions directly influence the behaviour of old bridges under current traffic loads. This paper focuses on assessing the influence of the design techniques on the load distribution and load-bearing capacity of reinforced concrete bridge girders. The load effects are estimated using 2D and 3D tools, and the paper analyses how this affects the structural resistance.

2 TOOLS FOR STRESS ESTIMATION

In past decades, engineers only had access to simplified methods for estimating the load effects on structures, and calculating load effects on bridges was especially challenging due to the live loads. Usually, a two-step 2D approach was used to determine the load effects on bridges, as shown in Fig. 1.

The first step was to position the live load on the deck cross-section, and by calculating the influence lines, estimate the load effects that would be applied to the bridge longitudinal configuration. The loads presented in Fig. 1 are based on NB 6 [8], and are positioned in the cross-section's most critical condition for each girder. The transverse load distribution calculated in a cross-section near midspan was assumed to be the same for all sections, even the ones close to the supports. Essentially, the cross-sectional loads were transferred to the longitudinal configuration of the bridge as point and distributed loads. The point loads represent the vehicle axles, while the distributed loads represent the crowd loads alongside the truck [9].

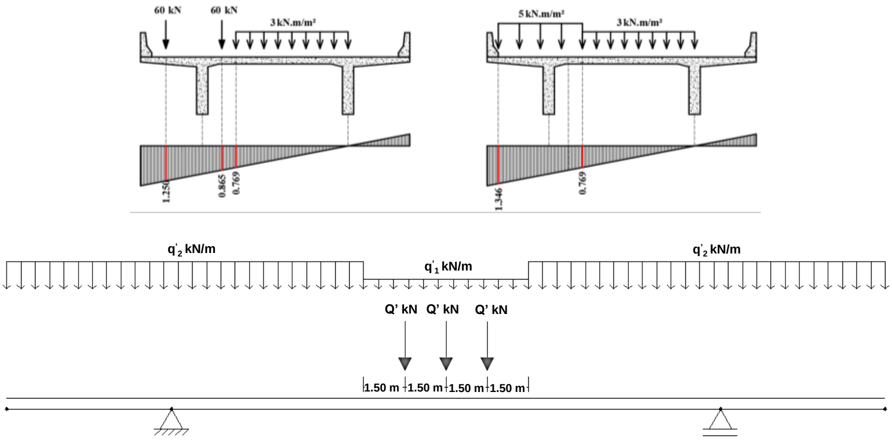


Fig. 1 2D procedure for the load effects estimative in bridges. Live loads and influence lines in the cross-section, and longitudinal loads.

For a long time, the theory of finite elements was developed mathematically, but with the increase in computer capacity, the finite element method has become the standard tool for identifying load effects in complex structures [10]. FEM allows for 3D load distribution, which yields better and more economical results [11]. Also, FEM is advantageous due to its flexibility of application, ease of use, and continuous increase in the computing power available to bridge designers [12].Fig. 2 shows an example of the 3D FEM approach for load distribution.

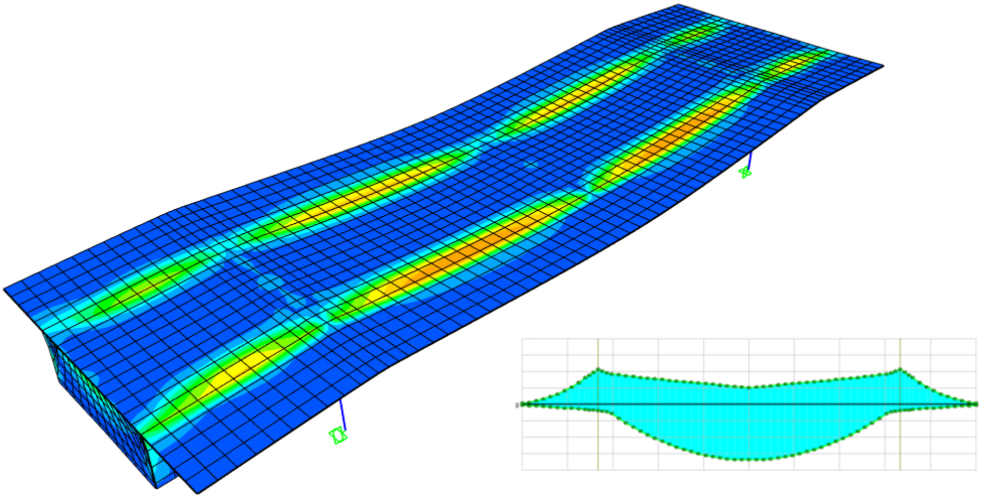


Fig. 2 3D Finite Element Model procedure for the load effects estimative in bridges.

3 CASE STUDY

Four existing bridges are analyzed in this paper to illustrate the influence of the design tools on load distribution. For each bridge, the load effects are obtained based on the 2D procedure and using the 3D finite element model. Then, these load effects are used to design the girders, and the actual load-bearing capacity according to current standards is calculated, as shown in Fig. 3.

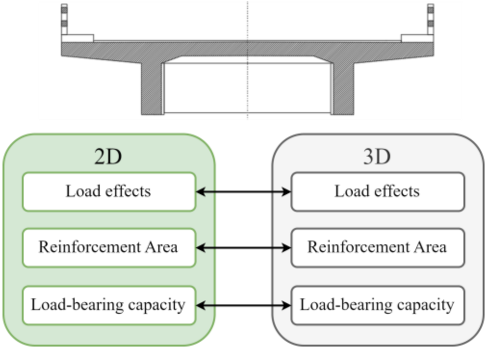


Fig. 3 Assessment procedure.

The chosen bridges are located in the state of Minas Gerais – Brazil, and were constructed between 1960 and 1985, as shown in Fig. 4. The deck configuration chosen for this analysis consists of reinforced concrete deck sections with two girders. Bridges with more than two girders were not considered because the transverse load distribution would differ from the others and could influence the results of this study, while two girder bridges exhibit simplified transverse distribution.

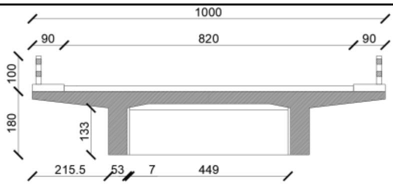
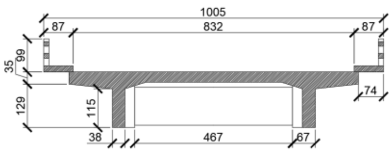
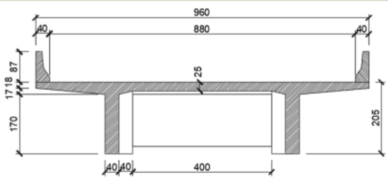
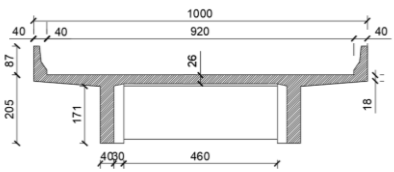
Bridge	Deck Section	Information
São João Bridge		Year: 1962; Design Vehicle Class: 36ton.; Length: 30 m; Span Length: 5/20/5 m;
Edson Passos Bridge		Year: 1963; Design Vehicle Class: 36ton.; Length: 22 m; Span Length: 4/14/4 m;
Teixeiras Bridge		Estimated Year: 1980; Design Vehicle Class: 36ton.; Length: 32 m; Span Length: 6/20/6 m;
Coimbra Viaduct		Estimated Year: 1985; Design Vehicle Class: 36ton.; Length: 100 m; Span Length: 6/22/22/22/22/6 m;

Fig. 4 Structural configuration of the bridges. Cross-sectional measures in mm.

3.1 Tools for load effects estimation

The stresses considered in this analysis are the positive bending moment, negative bending moment, and shear since they are vital for the girder's design. To emulate the original tools used for design, the 2D procedure in this work is conducted using the Ftool software [13], which is commonly used for the structural analysis of plane frames. The bridges analyzed in this paper were subjected to routine inspections, during which the cross-sectional and longitudinal dimensions were gathered. Based on the geometric configuration, the dead loads were calculated by considering the specific weight of concrete as 2500 kg/m³. The wearing surface loads were calculated by assuming a pavement thickness of 5 cm in the extremes of the lanes and 15 cm in the middle of the deck cross-section. The specific weight of the pavement was assumed to be 2400 kg/m³, equivalent to asphalt pavement. The live load configuration for the design of all bridges was the Classe 36 composition prescribed by the Brazilian standard NB 6 [8], which consists of a 36-ton. vehicle and two crowd loads: one of 5 kN/m² in front and at the rear of the vehicle and a second one of 3 kN/m² on the sides, as illustrated in Fig. 5.

The dynamic amplification factor for bridges constructed between 1960 and 1978 is 1.3 for spans up to 20m [14]. For bridges constructed between 1978 and 2003, it is given by Equation (1) [15].

$$\varphi = 1.4 - 0.007 \cdot \ell \geq 1.0 \tag{1}$$

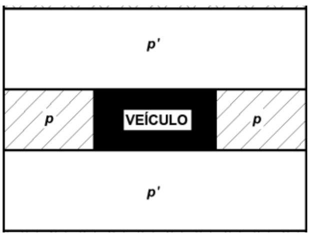


Fig. 5 Live load configuration – Classe 36

The 3D load distribution was obtained through CSIBridge v.23.3.1 [16]. The deck cross-section was modelled as a reinforced concrete T-beam, and the finite elements were shell elements. The concrete mechanical properties were estimated during the design procedure, which was conducted similarly to [7],[17]. The bearings were modeled according to each structure, and the calibration procedure considered the constraints of the superstructure through the bearings and their condition. The models' calibration was conducted by matching the vibration frequencies to those measured in the actual structure.

3.2 Structure Design and Load-bearing Capacity

Existing structures were designed following the standards applicable to their construction period. A detailed overview of the standards used for bridge design in past decades in Brazil can be found in [7]. In this case study, the bridges were built between 1960 and 1985; thus, the primary standards are NB 1 [18],[19], NB 2 [14],[20], and NB6 [8], which are focused on reinforced concrete structures design, bridge design and bridge live loads, respectively.

In this work, the load-bearing capacity of these structures is calculated according to the current standards, specifically NBR 6118 [21], which regulates the design of reinforced concrete structures.

4 RESULTS

The results of this case study will be presented first by comparing the load effects obtained by both design tools and then by estimating the load-bearing capacity of the bridges according to current standards. Thus, a complete redesign procedure will be conducted for each bridge based on 2D and 3D stresses.

4.1 Load distribution

The values of load effects on the bridge's girders are presented in the following tables, according to the tools, and separated by type of action. Table 2 presents the values of bending moment at midspan (positive moment). Table 3 presents the values of bending moment over the supports (negative moment), and Table 4 presents the values of shear strength.

Table 2 Values of positive bending moment.

Bridge	2D (kN.m)			3D (kN.m)		
	Dead	Live	Combined	Dead	Live	Combined
São João I	3211.6	2394.1	6323.9	3113.5	2022.8	5748.9
Edson Passos	1061.6	1343.8	2811.2	1046.0	987.1	2331.2
Teixeiras	2044.6	2342.6	6994.8	2295.0	1844.4	6466.61
Coimbra	1885.30	2175.9	6435.1	1841.3	1552.0	5285.1

Table 3 Values of negative bending moment.

Bridge	2D (kN.m)			3D (kN.m)		
	Dead	Live	Combined	Dead	Live	Combined
São João I	1301.2	1370.8	3083.2	1241.9	1358.0	3011.2
Edson Passos	767.4	929.1	1977.1	838.4	851.7	1947.2
Teixeiras	1740.5	1805.7	5622.0	1475.2	1618.5	4920.39
Coimbra	3265.2	1844.9	7789.5	3582.2	1471.0	7581.1

Table 4 Values of shear strength.

Bridge	2D (kN)			3D (kN)		
	Dead	Live	Combined	Dead	Live	Combined
São João I	895.8	518.2	1569.5	839.7	511.7	1506.35
Edson Passos	518.7	421.4	1067.4	535.5	374.5	1023.1
Teixeiras	754.3	513.3	1961.5	752.8	425.6	1830.31
Coimbra	883.9	583.1	2254.6	918.2	464.7	2096.2

In general, there is an overestimation of the combined values for all stresses. For dead loads, there is a general tendency for both procedures to yield similar results on average, with the mean 2D/3D ratio being 0.96, 1.03, and 0.99 for positive bending, negative bending, and shear, respectively. Individually, the Teixeiras Bridge stands out for exhibiting the higher variations, where the positive moment was underestimated by 11% while the negative was overestimated by 18%. The Edson Passos Bridge behaved similarly but with reduced variations. The results for the São João Bridge, both values were overestimated, whereas for the Coimbra Viaduct, both were underestimated.

The distribution of live loads showed a significant overestimation of positive bending moment values when calculated using 2D procedures, with an average increase of 29%. The negative bending and shear stresses were also overestimated by 12% and 15%, respectively. The overall overestimation of the live loads resulted in a mean overestimation of combined stresses of 13% for positive bending, 6% for negative bending, and 8% for shear.

In terms of absolute stress values, the Coimbra Viaduct differs from the other bridges as it is a multi-span bridge, while the others comprise a single span and two cantilever spans. This structural distinction considerably affects the bridge's behaviour, as the Coimbra Viaduct is primarily governed by negative moments, whereas the other bridges are designed mainly for positive moments. The more complex longitudinal configuration and influence line definition may help understand why this bridge exhibited the higher overestimation for live load stresses among all the bridges evaluated.

4.2 Load-bearing capacity

The next step in this analysis is to estimate the influence of the design tools on the reinforcement area and, consequently, on each structure's load-bearing capacity. The reinforcement area for 2D load distribution is estimated by reconstructing the original design plans of these structures, while for 3D loads, a design procedure is simulated. Table 5 presents the reinforcement areas for positive bending, negative bending, and shear.

Firstly, the São João and Edson Passos Bridges stand out by the high reinforcement areas. This could be explained by the reinforcing steel used in these bridges, 37-CA, which has a yield strength of 240 MPa, whereas the other two bridges use CA-50 steel, which has a 500 MPa yield strength. Another difference in design is that the shear reinforcement was comprised of the longitudinal bars inclined in a 45° angle distributed between the support and the middle of the span; thus, leading to the high values presented in Table 5.

Regarding the difference between 2D and 3D methods, the three stresses have higher mean areas for 2D design methods, all around 12% overestimation. However, the Coimbra Viaduct stands out for overestimating only the positive moment reinforcement and achieving the same area for negative moment and shear. Nevertheless, the 2D did not underestimate the reinforcement area in any situation.

Table 5 Reinforcement area

Bridge	2D			3D		
	Positive Bending (cm^2)	Negative Bending (cm^2)	Shear (cm^2/m)	Positive Bending (kN.m)	Negative Bending (kN.m)	Shear (kN)
São João I[1]	294.5	186.5	93.3	270	176.7	73.6
Edson Passos[1]	157.1	191.4	68.7	137.4	152.2	58.9
Teixeiras	108	103.1	20.9	98.2	88.4	20.9
Coimbra	98.2	166.9	20.9	88.4	166.9	20.9

Table 6 presents the estimated load-bearing capacity for bridges designed using both design tools. The increase in the load effects and reinforcement area also leads to an increase in the load-bearing capacity. All stresses assessed showed an overestimation when calculated using 2D procedures. When analyzing the bending moments, the capacity for bridges designed with 2D models is, on average, 10% higher for positive moments and 9% for negative moments. For shear, only the Edson Passos bridge presented any significative overestimation (11%), whereas the other bridges presented negligible differences.

Table 6 Load-bearing capacity

Bridge	2D			3D		
	Positive Bending (kN.m)	Negative Bending (kN.m)	Shear (kN)	Positive Bending (kN.m)	Negative Bending (kN.m)	Shear (kN)
São João I	9257.1	4577.5	2428.7	8537.3	4422	2417.2
Edson Passos	4097.1	4044.4	2273.8	3610.1	3415.2	2040.5
Teixeiras	7276.4	5678.5	1948.1	6650	5072	1948.1
Coimbra	6663.9	7878.8	2012.8	6027.8	7878.8	2012.8

Thus, based on the case studies presented in this work, bridges constructed in past decades have been shown to have an extra hidden capacity due to the tools used for estimating the load effects. This additional capacity is probably even higher than the one presented in this work due to the conservative design assumptions used in past decades, which may further enhance the load-bearing capacity of these structures. This means that these bridges can sustain higher loads than they were designed to carry, which could be one of the factors contributing to the safety of old reinforced concrete bridges.

5 CONCLUSIONS

This work evaluated the influence of the design tools on the load distribution and load-bearing capacity of reinforced concrete bridges designed in past decades. Based on the results obtained in this study, a few conclusions can be drawn:

- The estimation of dead loads is not significantly affected by the tools used for design. In some cases, this value was slightly underestimated by 2D tools.
- The estimation of live load is overestimated by 2D load distribution methods, especially the positive bending moments, which were overestimated by an average of 29%.
- When using 2D methods, the combined stresses are overestimated due to the impact factor, which increases the influence of the live loads.
- Bridges designed using 2D methods present an implicit extra load-bearing capacity due to the load distribution method's inherent conservatism, which may help explain how old bridges can sustain the current traffic loads.

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References

[1] Mascarenhas FJR, Carvalho RC, Vitório JAP. An analysis of the current conditions of bridges and viaducts of Brazilian highways. Anais do 61o Congresso Brasileiro do Concreto, IBRACON; 2019.

[2] FHWA. InfoBridge 2024.

[3] JSCE. Japan’s Infrastructure Grades 2020 & Introduction of Maintenance Technologies. 2021.

[4] DNIT. SGO - Sistema de Gerenciamento de Obras de Arte Especiais 2024. https://sgoinspetor.dnit.gov.br/sgo-inspetor/index.jsf?codItemMenu=1920 (accessed November 9, 2022).

[5] Mitre MP. Metodologia para inspeção e diagnóstico de pontes e viadutos de concreto. Dissertação (Mestrado). Escola Politécnica da Universidade de São Paulo, 2005.

[6] Guimarães R da S, Perlingeiro MSPL, Carneiro LAV, Júdice FM de S. Normas Técnicas Brasileiras sobre Projeto de Pontes em Concreto Armado: Considerações e Evolução. Brazilian Journal of Development 2020;6:77356–69. https://doi.org/10.34117/bjdv6n10-240.

[7] Cardoso MAN. Metodologia de avaliação da segurança estrutural de pontes de concreto armado. Dissertação de Mestrado. 2022.

[8] ABNT. NB 6 - Cargas móveis em pontes rodoviárias. 1960.

[9] Pfeil W. Pontes em concreto armado: elementos de projetos, solicitações, dimensionamento. Rio de Janeiro: Livros Técnicos e Científicos; 1979.

[10] Laggar L, Ström S. Load distribution in 3D structural analysis of a two girder concrete bridge An investigation of how different FE-modelling techniques influence sectional forces. Chalmers University of Technology, 2013.

[11] Cakebread T. The role of finite element analysis in bridge assessment and design. Bridge Maintenance, Safety, Management and Life-Cycle Optimization - Proceedings of the 5th International Conference on Bridge Maintenance, Safety and Management, 2010, p. 2440–6. https://doi.org/10.1201/b10430-369.

[12] FHWA. Manual for Refined Analysis in Bridge Design and Evaluation. 2019.

[13] Martha LF. Ftool - Two-Dimensional Frame Analysis Tool 2018.

[14] ABNT. NB 2 - Cálculo e Execução de Pontes de Concreto Armado. 1961.
[15] ABNT. NBR 7187 - Cálculo e Execução de Pontes de Concreto Armado. 1982.
[16] Computers and Structures Inc. CSIBridge 2024.
[17] Andrade MS, Cardoso MAN, Oliveira DS, Santos CFS, Ribeiro JCL, Carvalho JMF. The changes over time in the design criteria of reinforced concrete bridges according to Brazilian Standards. 64 Congresso Brasileiro do Concreto CBC 2023, Florianópolis: IBRACON; 2023.
[18] ABNT. NB 1 - Projeto e Execução de Obras de Concreto Armado. Rio de Janeiro: ABNT; 1978.
[19] ABNT. NB 1 - Cálculo e Execução de Obras de Concreto Armado. Rio de Janeiro: ABNT; 1960.
[20] ABNT. NB 2 - Cálculo e execução de pontes de concreto armado. Rio de Janeiro: ABNT; 1970.
[21] ABNT. NBR 6118 - Projeto de estruturas de concreto. Brasil: 2023.