Proposal of Conceptual Design of Prestressed Hollow-Core Slabs applied on Road Bridges

Sheila Stravate Leonel Esteves[1], Matheus Lorena Gonçalves Marquesi[2], Fernando Rebouças Stucchi[3]

[1]HMNC Engenharia - Polytechnical School of University of São Paulo,
[2]HMNC Engenharia - Pontifical Catholic University of São Paulo,
[3]EGT Engenharia - Polytechnical School of University of São Paulo.

Paulista Avenue, São Paulo, Brazil

Resumo

No Brasil, ainda que não de forma uniforme, grandes investimentos têm sido realizados para ampliação e modernização da malha rodoviária, que a tempos tem sido renegada. Consequentemente, as obras de arte especiais (OAEs) demandam concepções mais sustentáveis. Neste trabalho são apresentadas soluções potenciais para OAEs utilizando lajes alveolares protendidas. É valido ressaltar que esta concepção é ainda pouco explorada, desta maneira, são discutidos aspectos críticos ao dimensionamento dessas lajes para os exemplos propostos, especialmente em função da tipologia do carregamento. Como ponto de partida para este estudo exploratório, além de duas potenciais soluções de pontes com lajes alveolares, são apresentados características de experimentos coletados da literatura relativos à resistência a força cortante. Os autores identificam e trazem luz à necessidade de ensaios adicionais e específicos para representar satisfatoriamente a utilização de lajes alveolares em situações de cargas significativas concentradas.

Summary

In Brazil, although not uniformly, significant investments have been made to expand and modernize the road network, which has been neglected for some time. Consequently, road bridges require more sustainable designs. This paper presents potential solutions using Precast Prestressed Hollow Core Slabs in road bridges. It is worth noting that this design is still not well explored; therefore, critical aspects of the design of these slabs for the proposed examples are considered, especially concerning the loading typology. As a starting point for this exploratory study, in addition to two possible bridge solutions with hollow core slabs, characteristics of experiments found in the literature related to shear force resistance are presented. The authors identify and highlight the need for additional and specific tests to satisfactorily represent the use of hollow core slabs in specific load situations.

1 INTRODUCTION

Precast Prestressed Hollow-Core Slabs (PHCSs) are prefabricated concrete elements featuring pretensioned reinforcement and a cross-section with longitudinal voids. Their key characteristics—enhanced technological control, sustainability, reduced construction time, and versatility—make them highly advantageous for various structural applications. As industrialized components, PHCSs allow for precise quality control over materials and manufacturing processes. Their prefabricated nature significantly accelerates construction timelines, as they arrive on-site in their final form, eliminating the need for formwork and minimizing material waste. This enhances sustainability while also reducing labor and overall project costs. Additionally, their adaptability to different design requirements, produced in long casting beds and cut to specified lengths, adds to their versatility.

PHCSs have gained significant recognition, particularly for their technical feasibility in horizontal applications (such as floor slabs in multi-story precast structures) and vertical applications (such as precast closure panels). However, their use in infrastructure projects remains underutilized at a national level. Despite their strong potential for road bridge decks and port quay retrofitting, they are not yet widely adopted in these contexts. Expanding their application in infrastructure could unlock new efficiencies and cost savings in large-scale construction projects. In the buildings, the average span for hollow-core slabs in Brazil is 7.70 meters, with a maximum panel thickness typically reaching 30 cm. In countries where prestressed hollow-core slabs are a widely adopted construction system, this thickness can reach up to 700 mm, according to Albuquerque and El Debs (2005).

In road bridges, specific studies on the distribution of actions in the PHCSs are needed, especially on the behavior of hollow-core slabs under the loads inherent to their use in infrastructure projects. Additionally, research must address the required geometry to ensure the feasibility of this application. Given the potential for expanding the application of PHCs, there is a clear need to investigate the structural behavior of these elements with increased thickness, including details of transverse reinforcement at the ends to increase the shear capacity, which is a critical aspect for these slabs.

Thus, as a first step, this research aims to understand the variability of shear failure mechanisms observed in typical experimental tests, considering the load application points and the span of the element. Conceptually, the study focuses on hollow-core slab sections with heights exceeding 300 mm, with or without a structural topping, subjected to high-magnitude concentrated loads or partially distributed loads (as in road bridges). In the next stages, tests will be planned with specific characteristics to better represent this situation and to propose details that make this viable.

2 CONTEXTUALIZATION OF THEORETICAL AND TECHNOLOGICAL EVOLUTION FOR BUILDINGS UNDER UNIFORM LOADS

The recently published Brazilian Code ABNT NBR14861:2022 (Prestressed Concrete Hollow-Core Slabs - Requirements and Procedures) provides a distinction in the design of prestressed hollow-core slabs for cracked and non-cracked flexural regions, as it presents different prescriptions for calculating shear strength in each situation. Furthermore, the standard also includes criteria related to the application of concentrated loads on prestressed hollow-core slabs. It is worth noting that these considerations represent a significant advancement compared to the previous version of the same standard (NBR14861:2011).

Aligned with this, it is observed that in recent decades, there has been a constant increase in both height and span for prestressed hollow-core slabs. The data shown in Fig. 1 is related to applications with distributed load, and this span increase evolution is initially justified by the need to accommodate larger open spaces. However, this evolution in the production capacity of higher pieces reveals a new potential, which should be studied to enable the application of these more robust elements in larger-scale infrastructure projects.

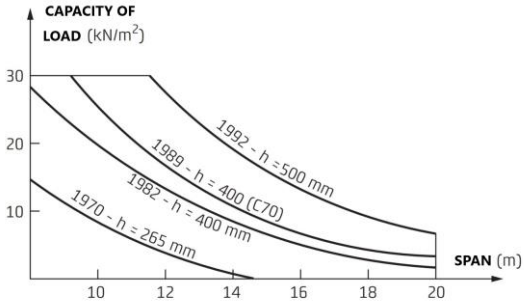

Fig. 1 Evolution of the relationship between load capacity, span, and depth of hollow-core slabs under uniformly distributed loads - ElDebs (2017) adapted from Janhunem (1996)

Linked to this in-depth conceptual development of the current NBR14861:2022 standard and the presented technological evolution of the relationship between span and depth in the implementation of prestressed hollow-core slabs is the opportunity to explore the constructive potential of prestressed hollow-core slabs through the evolution of understanding their structural behavior, supported by the state-of- the-art and new experimental tests.

In Spain, for example, there are already small-span bridges with decks made of prestressed hollow-core slabs. Some companies that manufacture these products have a specific line dedicated to bridge applications, including Corblock, Vialca, and Cirera. These companies indicate that typical construction arrangements generally consist of simple isostatic sections with spans of approximately 15 meters. The commonly used hollow-core slab heights range from 350 mm to 500 mm, while the thickness of the structural topping varies between 100 mm and 200 mm.

3 PHCS ROAD BRIDGES CONCEPTUAL DESIGN

ABCIC (Brazilian Association of Industrialized Concrete Construction) contacted all national suppliers of hollow-core slabs to understand the dimensions produced in the national context. Among the producers surveyed, only two reported manufacturing sections with heights greater than 300 mm, with the maximum dimensions being 405 mm for supplier 1 and 500 mm for supplier 2. The slab width for both producers was identical, measuring 1245 mm. Regarding the reinforcement of the section, both producers stated that it is possible to use up to 14 tendons of 12.7 mm, and, if necessary, some wires or tendons of 5 mm on the upper face of the element.

Based on this information about national production capacity, this work presents some conceptual designs for PHCS road bridge implementation. Since hollow-core slabs are manufactured on large prestressing beds, the length of the piece is not a limiting factor. However, the intended application presents a limitation due to forces as the structure's span grows. Compared to building spans, designs were initially developed with spans not exceeding 15 meters.

The proposed designs were conceived with hollow-core slabs arranged in both directions of the structure: longitudinally (3.1), considering various functional lane configurations that resulted in different total structure widths, and transversely, with a fixed structure width of 15 meters. On the other hand, the longitudinal length of the structure remains free, as the behavior of each panel in this direction is minimally influenced by the number of slabs placed along the longitudinal span (3.2).

By the provisions of NBR 14861:2022, the structural performance of hollow core slabs (HCS) in composite systems must account for the appropriate transfer of shear forces through longitudinal and transverse joints. Transverse interlocking, typically achieved through keys or webs, facilitates interaction between adjacent precast elements. Meanwhile, the interface quality between the HCS units and the cast-in-place structural topping largely governs longitudinal behavior. Given the composite nature of this connection, a thorough understanding of its fatigue behavior under cyclic loading is essential to ensure durability and structural safety throughout the system's service life.

3.1 Solution without girders (PHCS in longitudinal direction)

From the geometric properties provided by a supplier, along with the dimensions of Brazilian traffic lanes and the typical barrier, several conceptual bridge designs were developed with a 15-meter span and are composed of four PHCS in the transversal section.

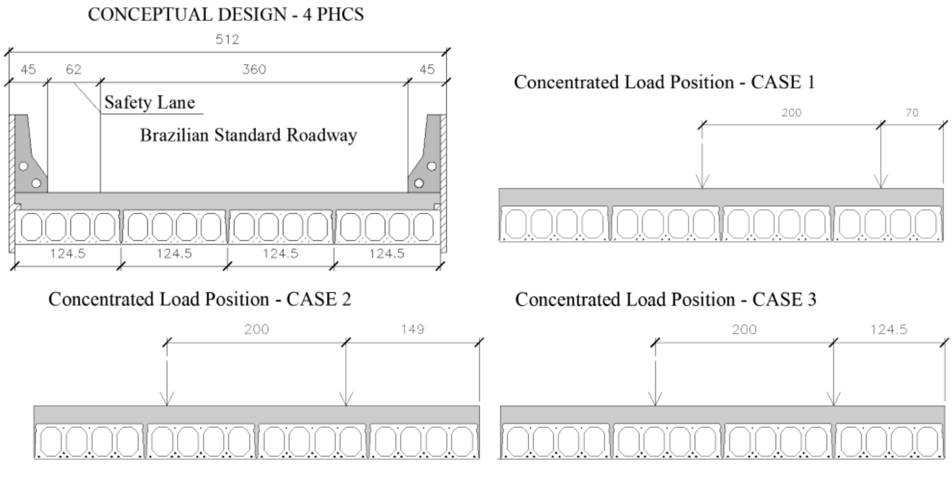

Fig. 2 Conceptual Design of Bridge using four PHCS in longitudinal arrangement and concentrated load positions

Case 1 illustrates the vehicle's position at the roadway's extremity near the barrier. Case 2 shows the vehicle positioned precisely in the middle of the transversal section, and Case 3 shows the concentrated load exactly in the junction of panels. This third case requires some special tests to understand the interaction between the concrete top and the PHCS section.

The representation of the concentrated load simplifies the actual load applied to the road bridge section, as in practice, the surface of the tires distributes the load across the deck. Therefore, the loading on the bridge can be interpreted as a partially distributed load, as shown in Fig. 3.

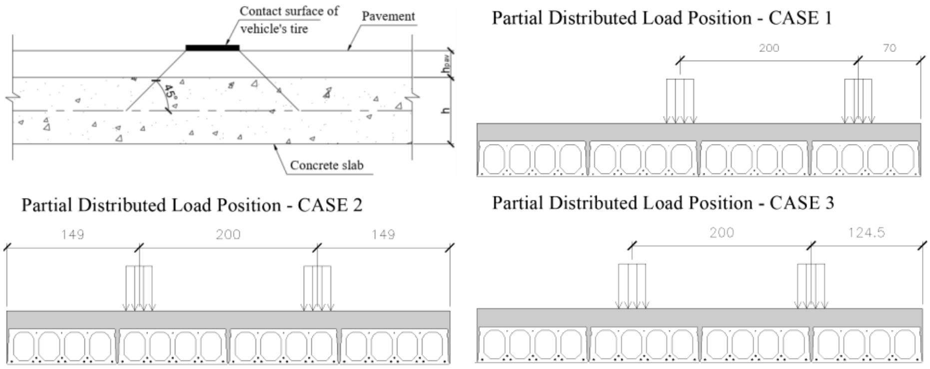

Fig. 3 Conceptual partial distributed load and load positions for longitudinal arrangement of PHCS

From the partially distributed load representation for cases 1, 2, and 3 above, it is possible to observe the importance of experimentally investigating the loading cases presented by the Brazilian standard NBR14861:2022, which includes some considerations regarding concentrated loads. Concerning the issue raised above, three hypotheses are proposed as potential factors for the failure of the element when subjected to concentrated loads: i) failure of the top slab section between the voids due to punching shear; ii) failure of the rib due to diagonal tension or shear, and iii) torsion interaction.

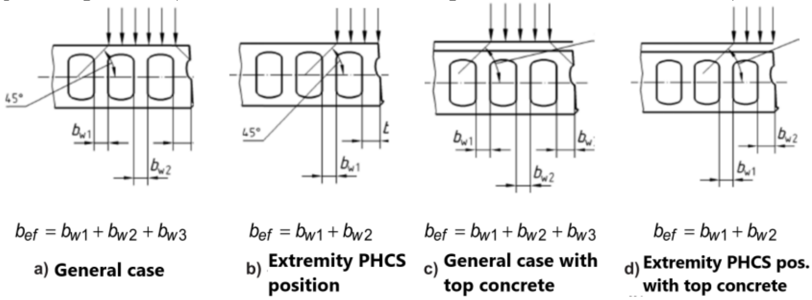

Fig. 4 Positions of concentrated load application on hollow-core slabs [NBR14861:2022]

The longitudinal position of the Type Vehicle TB-45 was designed to investigate the slabs' behavior under concentrated loads near the support. Analyzing concentrated loads at the mid-span of the element would be valuable for studying flexural behavior; however, since this was not the focus of the study, different designs were considered to understand their behavior in terms of shear, as this aspect is crucial for the design of PHCSs.

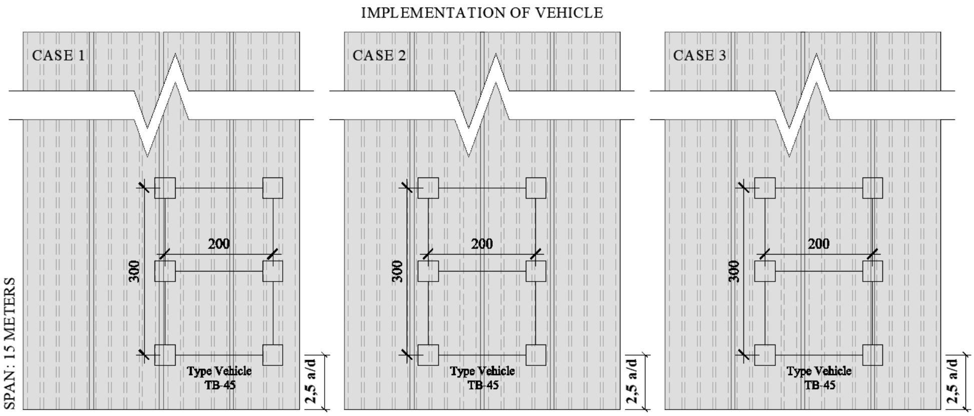

Fig. 5 Longitudinal idealized position of vehicle for critical shear

3.2 Solution with girders (PHCS in transversal direction)

Using the same geometric properties and traffic lane parameters applied in the previous conceptual design, the hollow-core slabs were positioned transversely to the bridge section while maintaining their original length of 15m. However, in this second conceptual design, because the slabs are oriented orthogonally to the traffic direction, the 11m central span and 2m of cantilever—previously a limiting factor for the bridge span—now define the width of the bridge deck, making the bridge span independent of the slabs themselves.

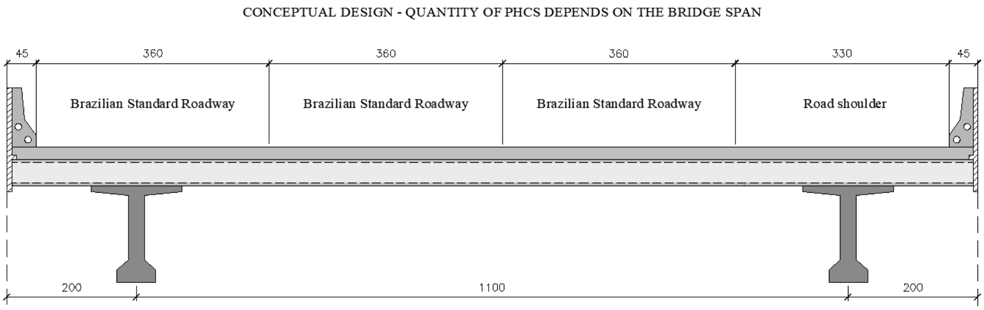

Fig. 6 Conceptual Design of Bridge using PHCS in transversal arrangement, [cm]

Overall, this second conceptual design enables the construction of longer bridges, as the panels are arranged sequentially along the bridge's longitudinal direction. However, the traffic width may pose a limiting factor, as the 15m length of the element—previously established for this conceptual study—now restricts the transverse direction of the structure.

Three idealized load cases were defined again for the TB-45 type vehicle. Along the longitudinal direction of the bridge, the first axle of the vehicle was positioned precisely over the axis of the hollow-core slab cross-section. Simultaneously, the load variations were applied across the bridge's transverse section. In case 1, the vehicle is positioned at 2.5a/d from the edge of the deck, representing an area with a high potential for shear failure due to diagonal tension. For case 2, the vehicle is placed exactly at the center of the deck's transverse section, where significant interaction between bending and shear forces is observed. Case 3 involves the vehicle's position at the edge of the deck, adjacent to the barrier.

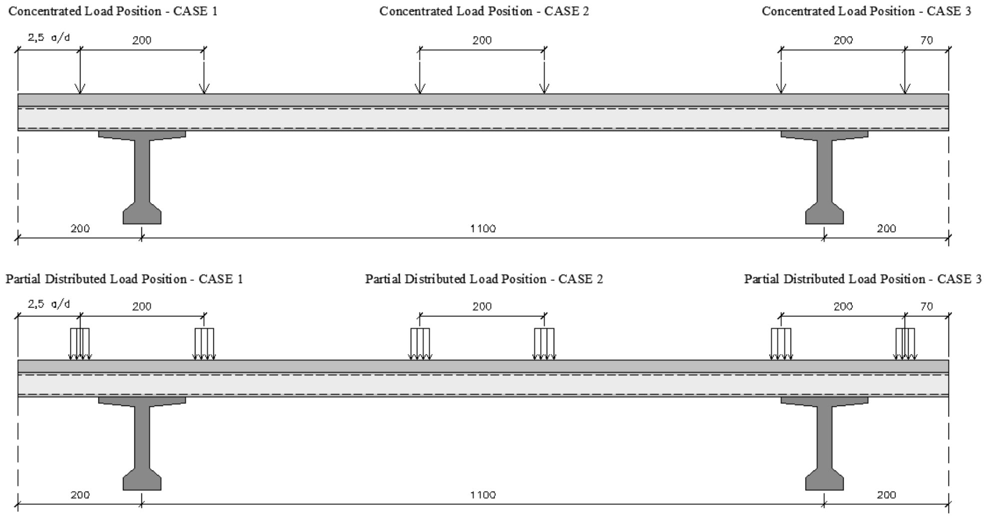

Fig. 7 - Concentrated load and partial distributed load position cases for conceptual design

4 TRANSVERSAL LOAD DISTRIBUTION

Another essential aspect to investigate in the arrangement of both conceptual designs is the transverse load distribution among the PHCS elements that comprise the section. The presence of the structural top is vital for the uniformity of the panels; particularly for sections subjected to concentrated loads, it plays a key role in mitigating the effects of loading when applied directly to the slab connecting the webs between the voids. Consequently, it is imperative to conduct experimental tests to assess the extent to which the top concrete contributes to the uniform distribution of stresses between the webs and the potential increase in the load-bearing capacity of the composite element. In this context, it is also crucial to evaluate the bond between the structural top and the hollow-core slab.

The NBR14861:2022 standard presents three graphs illustrating the percentage of load distributed to each slab, considering an arrangement of five slabs positioned in the previously described longitudinal configuration. Based on these load distribution percentages, it is possible to calculate the longitudinal shear force at each joint and the torsional moments in each element. Abacus I presents the load distribution for linearly distributed loads along the longitudinal axis of the element (Fig. 6a). Abacus II illustrates the load distribution across each hollow-core slab for concentrated loads applied at mid-span and centered on the section's transverse axis (Fig. 6b). Abacus III also depicts the load distribution resulting from a concentrated load positioned at mid-span; however, in this case, the load is applied at the edge of the section in the transverse direction (Fig. 6c).

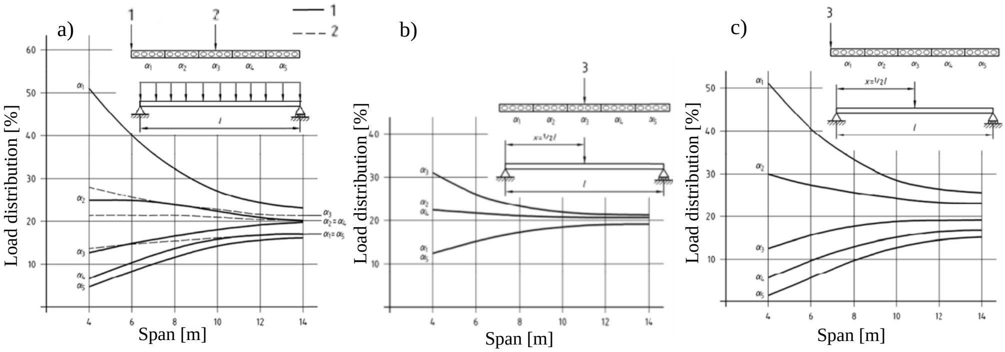

Fig. 8a Load distribution factors for linear actions at the center of the slab span, at the center, and on the side of the pavement **Fig. 8b** Load distribution factors for a point load at the center of the slab span **Fig. 8c** Load distribution factors for a point load on the side of hollow-core slab pavements – [adapted from NBR14861:2022]

Although these graphs provide guidance on the transverse distribution of forces, certain limitations in load distribution hinder their direct application in the design of road bridges using PHCS. The primary concern is the potential for multiple load positions in the element's transverse and longitudinal directions. Furthermore, as illustrated in Fig. 5, in the longitudinal direction, multiple concentrated load points may occur, some of which can be positioned closer to the support rather than strictly at the mid-span of the element.

5 EXPERIMENTAL DATABASE ON SHEAR FAILURE OF PHCS

Based on the writings explored to investigate the state-of-the-art, experimental shear failure test data were collected from prestressed hollow core slabs. The data presented by Bertagnoli and Mancini (2009) were initially gathered. Later, additional data were collected from the scientific works of UDA (2003), Tawadrous and Morcous (2017), TNO (2005), Palmer and Schultz (2010), Palmer and Schultz (2011), Pajari (2005), and Masini (2005).

The test table presented by Pajari (2009) was adopted to classify the test arrangements, and additional scenarios were included for cases that did not fit within the author's description. The numbering for these additional scenarios follows the sequential order previously established by the author (Fig.10). The distribution of tests by loading scenario is presented in Fig. 9.

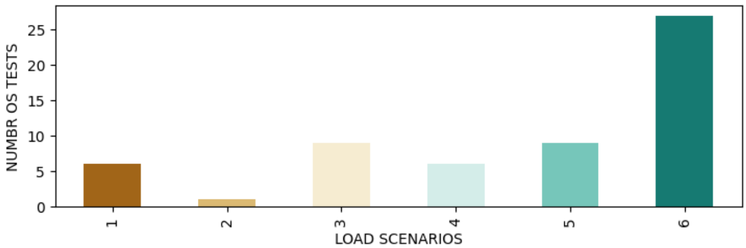

Fig. 9 Distribution of experimental data by load scheme presented in Fig. 10

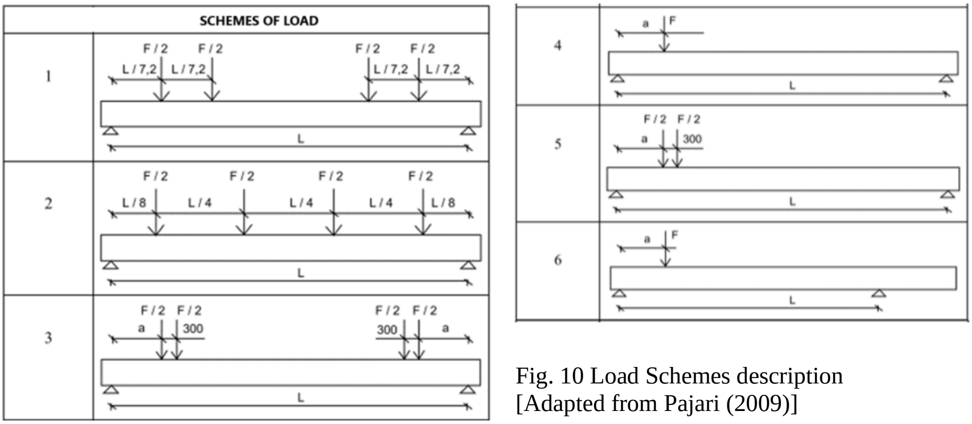

Fig. 10 Load Schemes description
[Adapted from Pajari (2009)]

Among the obtained parameters, the ratio between the distance from the load application point to the support axis (a) and the slab thickness (d) stands out, as it is crucial for the transition between potential rupture phenomena. Therefore, the distribution of values for this variable was investigated and can be observed in the histogram and its respective density curve in Fig.11. It is noticeable that most of the tests show a relationship of $2 \leq a/d \leq 4$, with 37% of the tests presenting a relationship of $a/d = 2.50$.

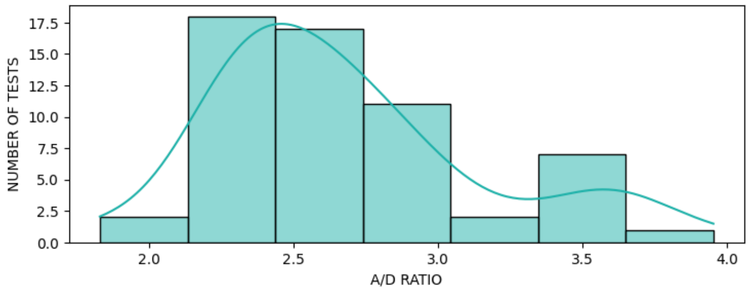

Fig. 11 A/D Ratio Distribution - Experimental Database

6 RESULTS AND DISCUSSIONS

The proposed conceptual designs show that, even in a simplified context, such as in the present article, various possible loading scenarios arise due to the variation in the traffic load's position over the deck section. Conversely, it is also clear that the loading scenarios from the literature do not encompass the necessary load cases to fully grasp the actual behavior of PHCS applied to road bridges.

Additional tests are necessary beyond those previously conducted to validate the actual behavior of prestressed hollow-core slabs under concentrated loads. This is because, in the preliminary phase, the applied load was uniformly distributed across the element's cross-section. Furthermore, another important consideration is the presence of the structural topping and its contribution to the uniform distribution of forces between the webs. However, assessing the bond between the structural topping and the hollow-core slab is essential in this context.

In summary, given the significant potential for bolder applications, the broader use of prestressed hollow-core slabs in Brazilian infrastructure is essential, as they provide an innovative solution to accelerate construction, reduce costs, and enhance the durability of structures, aligning with global trends in industrialization and sustainability within the construction industry.

References

[1] ABNT-NBR14861. Lajes alveolares pré-moldadas de concreto protendido — Requisitos e Procedimentos. [S.l.]: ABNT, 2022.
[2] ELDEBS, M. K. Concreto pré-moldado: fundamentos e aplicações. [S.l.]: Oficina de Textos, 2017.
[3] HAWKINS, N. M.; GHOSH, S. K. Shear strength of hollow-core slabs. PCI Journal, p.110–114, 2006.
[4] PAJARI, M. Resistance of prestressed hollow core slabs against web shear failure. 2005. Available: ⟨http://www.vtt.fi/inf/pdf/⟩.
[5] PALMER, K. D.; SCHULTZ, A. E. Factors affecting web-shear topacity of deep hollow-core units, 2010.
[6] PALMER, K. D.; SCHULTZ, A. E. Experimental investigation of the web-shear strength of deep hollow-core units. 2011.
[7] TAWADROUS, R.; MORCOUS, G. Shear strength of 16 in. thick hollow-core slabs. In: PCI Convention and National Bridge Conference. [S.l.: s.n.], 2017.
[8] TAWADROUS, R.; MORCOUS, G. Shear strength of deep hollow-core slabs. ACI Structural Journal, American Concrete Institute, v. 115, p. 699–709, 5 2018. ISSN 08893241.
[9] TNO. TNO Building and Constructions Research, TNO Report: Standard Shear Tests on Prestressed Hollow Core Slabs according to EN1168, Hague, 2005. 2005.
[10] UDA. Prove di carico statico su solai alveolari Spiroll-Report of Generale Prefabbricati.[S.l.]: Universita' Degli Studi di l'Aquila, 2003.