Federal University of Paraiba

Center of Technology

POST-GRADUATION PROGRAM IN CIVIL AND ENVIRONMENTAL ENGINEERING

– MASTER'S DEGREE –

NEW INTERFACES FOR A CONNECTION BY ADHERENCE IN COMPOSITE STEEL-CONCRETE STRUCTURES

By

Lisarb Henneh Brasil

Master's Dissertation presented at Federal University of Paraiba in order to obtain master's degree in Civil Engineering

João Pessoa – Paraiba **August, 2019**

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A thesis submitted in partial fulfilment of the requirements for the Degree of Master of Engineering in Civil Engineering at Federal University of Paraiba.

Candidate: Lisarb Henneh Brasil

Advisor: PhD. Hidelbrando José Farkat Diógenes

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LISARB HENNEH BRASIL

NEW INTERFACES FOR A CONNECTION BY ADHERENCE IN COMPOSITE STEEL-CONCRETE STRUCTURES

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2019

I dedicate to myself.

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ABSTRACT

The technical and economic development of structural alternatives in building construction is a continuous demand. Despite the large number of studies conducted each year, few are dedicated to establishing rigid methodological criteria in order to assess their relevance to the progress of science. Thus, the purpose of a systematic review (SR) may be to discuss data, opinions or practices, provide a survey of previous publications, critique the current work, or make summary projections about future discoveries. In this way, this paper presents a SR related of the structural behavior of Connections by Adherence, aiming to discuss concepts, major findings and research methods employed, which allowed us to infer that the connectors present sufficient shear resistance and ductility so that it can be applied to several types of composite structures, mainly in buildings construction. Furthermore, experimentally evaluates the applicability of connection by adherence between steel and concrete in the context of ribbed slabs. For this purpose, Push-out specimens were fabricated and performed in accordance with Eurocode-4 requirements, where the connection behavior is analyzed in terms of its load-slip relation and the failure modes are identified. All the results allow to induce that the Connector by Adherence made with checkered steel plate is appropriate to use in composite structures, as it certainly exhibited satisfactory performance in terms of ultimate shear resistance and ductility.

KEYWORDS: *Composite Structures; Shear Connector; Prefabricated; Building Construction.*

RESUMO

O desenvolvimento técnico e econômico de alternativas estruturais na construção civil é uma demanda contínua. Apesar do grande número de estudos realizados a cada ano, poucos se dedicam ao estabelecimento de critérios metodológicos rígidos, a fim de avaliar sua relevância para o progresso da ciência. Assim, o objetivo de uma revisão sistemática (RS) pode ser discutir dados, opiniões ou práticas, fornecer um levantamento de publicações anteriores ou fazer projeções resumidas sobre descobertas futuras. Dessa forma, este artigo apresenta uma RS relacionada ao comportamento estrutural das Conexões por Aderência, com o objetivo de discutir conceitos, principais evidências e metodologias de pesquisa empregados em estudos primários. Com isso, permitiu-se inferir que os conectores apresentam resistência ao cisalhamento e ductilidade suficientes para que possam ser aplicados a vários tipos de estruturas mistas de aço-concreto, principalmente na construção de edifícios. Além disso, avalia experimentalmente a aplicabilidade da conexão por aderência entre aço e concreto no contexto de lajes nervuradas. Para esse fim, modelos de Push-out foram fabricados e ensaiados de acordo com os requisitos do Eurocode-4, onde o comportamento da conexão é analisado considerando principalmente a relação carga *x* escorregamento (load *x* slip). Além disso, os modos de ruptura dos modelos foram investigados. Desse modo, todos os resultados permitiram induzir que o Conector por Aderência fabricado com chapa de aço tipo Xadrez é apropriado para uso em estruturas mistas de aço-concreto, pois certamente exibiu desempenho satisfatório em termos de resistência ao cisalhamento e ductilidade.

PALAVRAS-CHAVE: *Estruturas mistas; Conector de cisalhamento; Pré-fabricado; Construção de edifício.*

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CHAPTER 1

INTRODUCTION

1.1 Context and motivation

Economical, constructional, and mechanical advantages presented by the steel-concrete composite structures, enables them to be used in wide range of applications in civil engineering. The advantages provided by the composite structures are desirable when seeking to rationalize the construction, it means, simple, fast and economical constructions that can satisfy the customer's demands for quality, aesthetics and cost.

Thus, solutions optimized based on traditional construction system have been a constant target of research, as seen in [1], [2] ,[3], [4], [5], among which stand out the steel-concrete composite structures related to precast construction. In the precast construction industry, a whole or part of the structural elements may be produced in an industrial environment, which characterizes a greater constructive agility with a high quality.

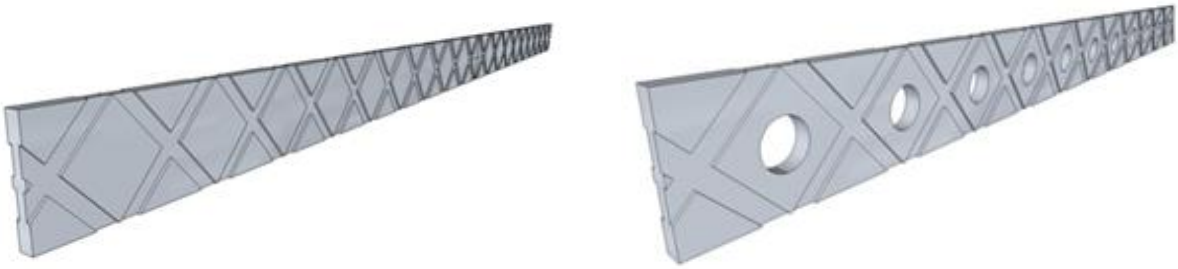
Steel and concrete composite structures combine the favorable properties of both materials ideally by positioning the concrete in the compression zone and the steel in the tension zone. Therefore, an adequate shear transfer is always desirable to ensure the composite action in the structure, which according to Valente [6] can be obtained by reducing or preventing the relative displacement of steel and concrete sections at their interface, and shear connectors are used to provide it.

Previous studies indicates that the headed stud is the most common type of mechanical shear connector, despite of several disadvantages related to its use in prefabricated structures Papastergiou [2], thus the development and enhancement of new types of connectors is necessary to in order to ensure a rational and safety use.

In this context, connection by adherence, originally studied in depth by [7], seems to be very promising for reducing the time of construction, improving the durability of the system without to increase cost of the solution [3].

According to [8] and [2], the advantages of connections by adherence result from their high resistance to shear, which provides a high level of connection on the composite section. This resistance comes from the shear stress development on the interfaces among the elements.

Diógenes [3] studied and assessed some connectors, as such R and RP-type (Figure 1), with the objective of finding an easy way to produce shear connections in prefabricated elements and to adapt this new connection technology to the Brazilian market. Basically, the innovative connection proposed, comprises an embossed steel plate welded longitudinally to the upper flange of the steel girder. The deck consists of precast reinforced concrete (RC) segments as presented in Figure 2.



R-type RP-type

Figure 1. Linear Connectors by [3].

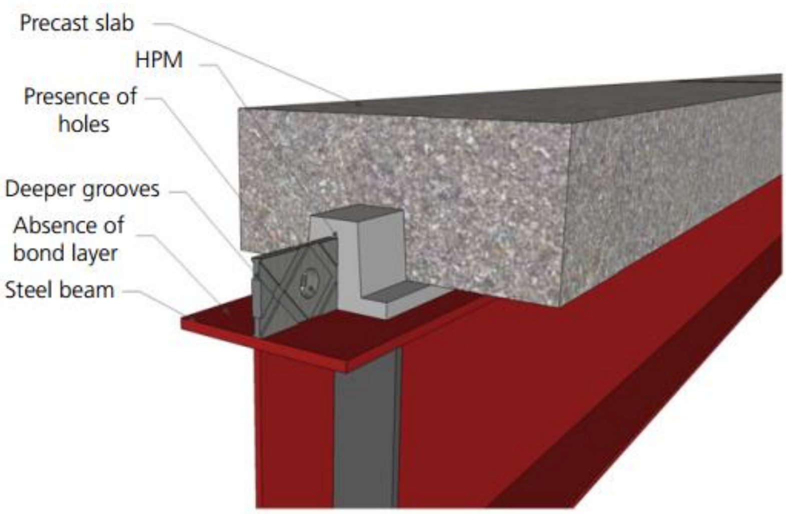


Figure 2. Innovative connection (adapted from [3]).

It is known that in the building construction with composite structures in Brazil, three types of slabs are normally used, being the slab with the form of steel incorporated (Steel Deck system), the solid slab cast in loco and the ribbed slab made by lattice joist. According to David [9], this first type of slab has advantages over solid slabs, providing economic viability in large-scale works.

In this context, Neves [4] addressed in his research, through an experimental and numerical approach, the use of connections by adherence in composite steel-concrete structures where the Steel Deck structural system is used (or similar), presenting satisfactory results in terms of shear resistance and maximum load capacity of the connection proposed, among other parameters.

In order to follow up the research developed by Neves [4], Fernandes [10] performed experimental tests of push-out and on steel–concrete composite beams and concluded that – among others remarks in order to ensure the viability this solution for beam slab connection, it will be necessary to continue researching and analyzing the performance of this type of connection.

In turn, the slabs ribbed made by lattice joist have been widely used in metal structures, being liable to work in low and medium size works. However, there is a need to know more about its structural behavior, which includes its interaction with the rest of the structure, i.e., the study of the connection [9].

Ribbed slabs may be cast in loco or precast rib slabs, the tensile zone for positive moments being in the ribs between which inert material may be placed, like EPS blocks (expanded Polystyrene) or ceramic tile. According to the arrangement of the ribs, these slabs can be classified as one-way slabs and two-way slabs. The reinforcement of ribs are formed by the presence of lattice joist, which is a structure formed by electrofusion system, where two trusses joined by a bar at the top vertex, with lower longitudinal bars that constitute the reinforcement of the tensile zone. The main advantages of ribbed slabs are low volume of concrete (although the slab’s overall depth is bigger), reduced dead weight and improvement of formwork system for casting, facilitating assembly and streamlining work.

Thus, considering that this field of research is still incipient with respect to the variability of geometries and constructive dispositions, it is evident the scientific and market interest in mastering the structural behavior of composite structures using Connections by Adherence.

However, as the types of composite structures become more varied, the mechanical behavior of the shear connection gets more complex, the design and construction get more constrained, and higher workability on the construction site is required [11].

The structural response of the connector by adhesion is influenced by several geometric properties, such as number of holes, plate height, length and thickness, concrete compressive strength and the presence and percentage of transversal reinforcement present in the slab of concrete. Consequently, the technical and economic development structural alternatives in building construction is the motivation to develop this systematic review about shear transfer in composite structures which use connectors by adherence.

It is believed that a comprehensive and systematic review (SR) of the literature related to the Connection by Adherence applicable to civil construction is important for the scientific progression on this subject, including the use of these in the construction of buildings since they have not been the main focus of researches until nowadays.

It should be noted that the SR's are different from the traditional literature reviews, once they seek to group all the evidences that fit the pre-specified eligibility criteria to address a specific research question, with the aim of minimizing prejudice by providing an audit trail of decisions, procedures and reviewers' conclusions [12,13]. Furthermore, the scope and structure of SR in any field of study varies based on its purpose.

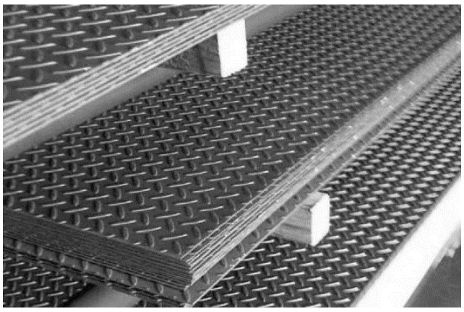
When a comprehensive bibliographic research is conducted transparently, impartially and logically, it can be considered a "Systematic Review" [14]. With this, methodological rigor increases and helps to develop a reliable knowledge base from a variety of sources [15]. Thus, the purpose of a review may be to discuss data, opinions or practices, provide a survey of previous publications, critique the current work, or make summary projections about future discoveries [12].

1.2 Objectives

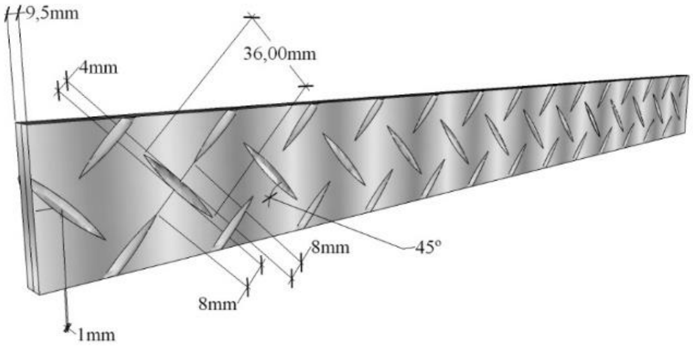
Through a systematic review of the literature, this paper aims evaluate how the Connection by Adherence are applicable to building construction. In order to achieve the research general objective, the following specific objectives were established:

- To discuss concepts, major findings and research methods employed;
- To synthesize evidence about Push-Out tests, which includes main idea application of the connection, maximum load capacity, ductility and crack patterns.

Furthermore, experimentally evaluates the applicability of connection by adherence between steel and concrete in the context of ribbed slabs, in order to offer, in a propositive way, foundations to researchers and engineers of structures regarding the use of these connections in home and small buildings. Evaluating and discussing aspects of the structural behavior of these connection, using linear connectors formed by ASTM - A36 chess type plate, as presented in Figure 3.a and Figure 3.b.



(a)



(b)

Figure 3. (a). Chess type plate; (b). Linear connector formed by chess type plate welded *“back-to-back”*

1.3 Methodology

The methodology proposed in this study consists of two steps: a systematic review and an experimental program. Both approaches refer to the study of evidence related to Push-out essays, but present independent discussions, which allows the analysis in question from two different perspectives.

In the systematic review of literature step, relevant studies were selected through database search criteria, inclusion criteria for the studies to select them, and criteria for evaluating the methodology and results of these, on the topic concerning connections by adherence from linear connectors in steel-concrete composite structures. This review made it possible to judge the possible use of this type of connection in building construction through evidence already present in primary studies.

The experimental program was conducted at the Structures and Materials Laboratory - LABEME located at the Federal University of Paraiba - UFPB. It consists of conducting material characterization tests together with Push-out tests to analyze the mechanisms and surfaces of rupture and determine the ultimate shear strength.

CHAPTER 2

SYSTEMATIC REVIEW

SR's vary in scope, quality, and relevance and may seek to expand on existing data by pooling results in a way that provides a higher degree of certainty, less error, or answers an entirely new question using existing data. A clear outline of the steps undertaken in a review can provide the transparency needed for replication, as well as appropriate updates when additional data are generated in future studies. Zumsteg et al. [16] recommend that, at a minimum, a SR's protocol include five key components:

I. a general description of how studies or data will be discovered for consideration of further review (e.g., literature or database search, manual review of the bibliographies of key publications, previous studies performed by the author's laboratory, solicitation of unpublished data);
II. enough information about any electronic search strategies that the search can be replicated;
III. clear parameters describing how the decision will be made to include or exclude individual studies and data for further analysis in the systematic review and/or meta-analysis;
IV. a clear plan for recording and summarizing data from the individual studies, including what parameters or data points are of interest;
V. if any, meta-analyses are planned.

In order to simplify, an acceptable concept for SR is a structured evaluation of the literature, aiming answer a specific research or application question, associated with a synthesis of the best available evidence.

2.1 Methods

2.1.1 Planning the review

Previously, a group of four researchers were invited to contribute to the research protocol, being two Experts – authors which are professors – on the topic of this paper. This protocol specifies in advance the process of identifying relevant searches, e.g., how the identified search will be filtered. In this case, the research question, the search strategy and criteria of exclusion were defined and also the method of synthesis. So, according to the main objective and scope of this SR, the proposed research question was: *Can Connection by Adherence be effectively applied in building constructions?*

2.1.2 Study identification

This process was initiated building a comprehensive set of search terms that relate to connections on composite structures. These were concatenated into a search string using a series of Boolean 'AND' and 'OR' operators. No language limit was applied. All other search refinement options have not been changed. The Web of Science® database was adopted using the strategy presented in Table 1.

The study of Connections by Adherence, between steel–concrete composite structures, is relatively new. In 2002, the Steel Structures Laboratory of EPFL in Switzerland associated with the engineering bureau DIC Engineers began to develop an innovative connection for the beam–slab connection, which they called "Connection by Adherence" [17]. Thus, the researches were carried out between the years of 2002 and 2018 and carry out through January to May of 2018. These citations were downloaded and exported to the reference manager Mendeley® for the selection of studies.

About the research #4, presented in Table 1, it should be noted that Connection by Adhesion, Interlocking and Friction, is an alternative name for Connection by Adherence proposed by [18].

Table 1. Search strategies in the database.

Researches	First field	Operator	Second field
1	Connection by Adhe* "OR" Shear connec*.	AND	Steel-concrete composite "OR" Structure composite "OR" Composite beam.
2	Perfobond connector "OR" Perfobond rib connector "OR" Perfobond shear connector.		
3	Y-shaped "OR" T-shaped "OR" I-shaped "OR" Y-type "OR" T-type "OR" I-type "OR" "CR connector" "OR" Crastbond.		
4	Interlocking "AND" Friction "AND" Adhesion.		

2.1.3 Study selection and quality assessment

The selection process began by selecting potentially relevant articles through a title and abstract scan of citations. After that, the duplicated citations and citations that explicitly matches with the exclusion criteria were exclude from the SR. The exclusion criteria, which are directly related to the research aim, were developed to describe the types of study eligible to be in-depth review. The criteria itself are listed in Table 2.

Table 2. Exclusion criteria.

No.	Criteria	Reason for exclusion
1	Just article and review as document types	Other types may not be relevant
2	*Qualis* - CAPES higher than B1 or have a JCR	a. Quality and Validity of research b. To reduce biased data synthesis
3	Full-text articles unavailable electronically	Resources and time aren't available to gather them
4	Non-English language	May not have relevance and widely disseminated academically
5	Do not address Push-Out tests	Push-Out tests are the focus of the article
6	Do not address linear connectors	Linear connectors are the focus of the article

The researches – authors which are students – screened the articles according to pre-specified inclusion and exclusion criteria, and independently extracted the data. Any disagreements were been resolved by consensus the experts.

Some strategies to decide whether it is appropriate to include them in a SR are adopted, especially if the focus is methodological procedure, compliance, and data reliability. For this, criteria were adopted to evaluate the quality of the study in order to ensure that sufficient rigor has been applied to the conduct of each research. Thus, the quality of the studies was initially determined according to the parameters and procedures used by CAPES[1] for the stratification of the quality of scientific production, named *Qualis*. In a second way using the JCR (*Journal Citation Reports*), a statistical base from Thomson Reuters. So, to be included in the research, the reference needed to present a *Qualis* higher than B1 or have a JCR.

2.1.4 Data extraction and synthesis

In SR, the duplicate data extraction is a common feature designed to improve reliability, increase accuracy and validate data interpretation. Thus, the reviewers independently assessed each item included. Each one extracted the data in a table of predefined evidences. Subsequently the two tables were compared, and any disagreements were resolved through discussion between the expert(s).

The qualitative and quantitative data collected in each study include: main idea of study; methodological procedures adopted in the experimental program, including characteristics of materials and description of the connector(s) and/or connection; values of the maximum load capacity of the connection; parameters which evaluates the connection ductility; evidences (main discussions) about cracking patterns and modes of failure; evidences about ductility and shear bond strength; main conclusions about ductility and resistance of the respective connections.

It should be emphasized that the data categorization was based on the similarity of meanings, e.g., to explore them in the search for consistent patterns and/or systematic relationships between variables.

A meta-study approach was used to synthesis the studies in order to address the research questions. This approach involving analysis of theory, methods and findings in qualitative research, and the synthesis of these insights into new ways of thinking about the phenomenon

[1]Higher Education Personnel Improvement Coordination (CAPES) is a foundation linked to the Ministry of Education (MEC) of Brazil engaged in the expansion and consolidation of graduate studies (masters and doctorate) in all states.

creates a mechanism by which the nature of interpretation is exposed and the meanings that extend well beyond those presented in the available body of knowledge can be generated [19].

Meta-study is seen as an interpretative process, which attempts to preserve the context of the original research, and place greater emphasis on theory building as the purpose of synthesis, enabling researchers to identify and compare themes emanating from the studies. The aim is to transform the accumulation of findings into a "legitimate body of knowledge" with the ultimate aim of generating new theory [19].

2.1.5 Outcome measure

In this stage, the results concerning the previously defined parameters regarding the Push-Out tests performed by the respective selected works were qualitatively evaluated. In this way, we evaluated evidences that deal with the maximum load reached by the models, the ductility and cracking characteristics of the respective models. In this sense, were tried to synthetize the evidence in order to answer the desired scientific question presented in 2.1.1.

2.2 Results and discussion

The initial search recorded 2.454 studies in the database, which 2.083 documents were recorded in step 1, 291 documents in step 2, 75 in step 3 and 05 in step 4. By title and abstract, 473 studies potentially relevant to the SR were selected. After that, the duplicated records were removed, finally 322 studies remained. Therefore, the subtotal of 322 studies was evaluated according to the eligibility criteria. 17 articles, in the end, met the inclusion criteria and were added to the SR, in order to be analyzed carefully. Figure 4 presents the flow diagram of studies search and Table 3 describes the results.

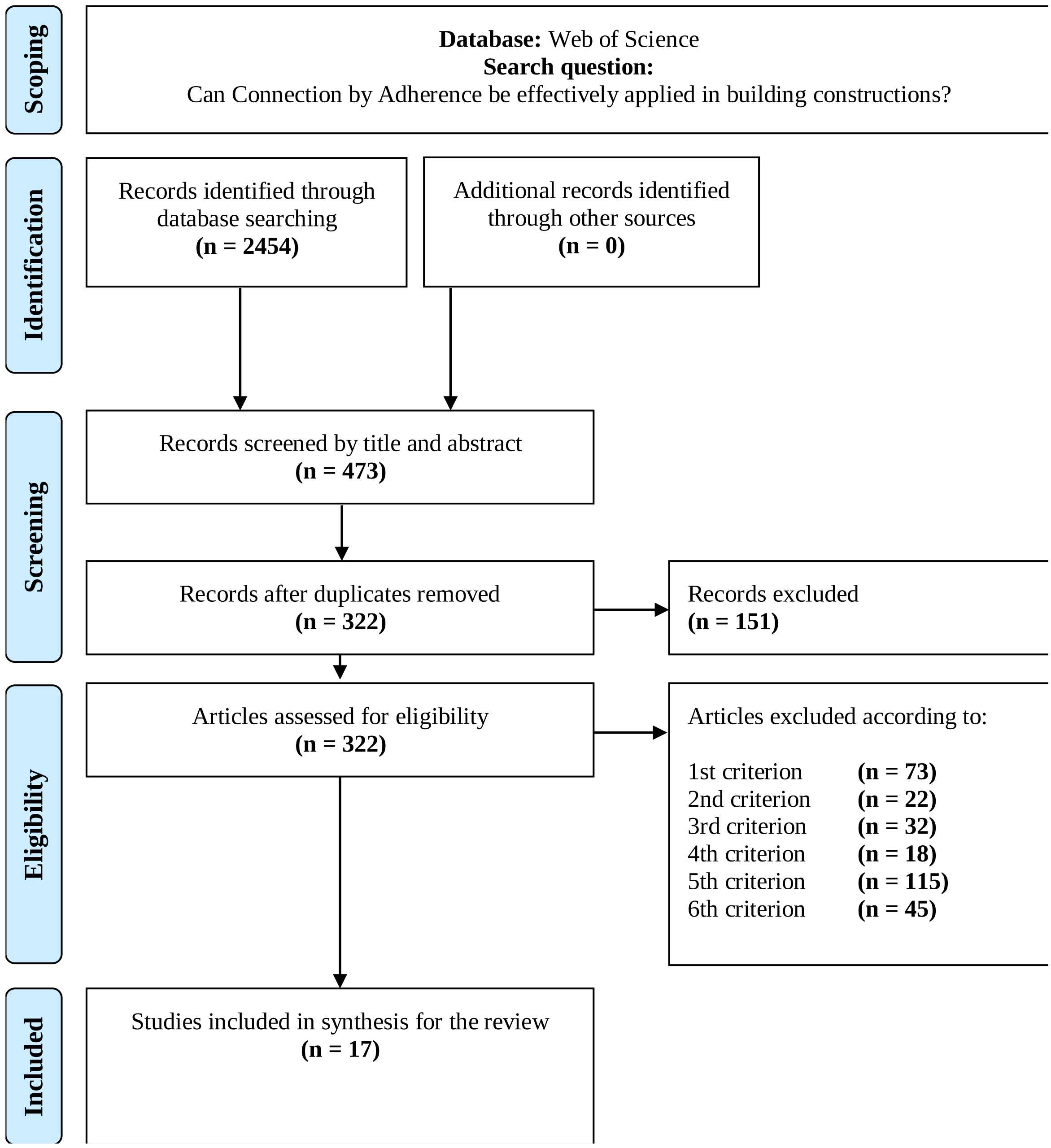


Figure 4. Flowchart of the systematic review process.

Table 3. Selected studies.

Ref.	Citation	Title
[20]	Kim and Jeong, 2006	Experimental investigation on behavior of steel-concrete composite bridge decks with Perfobond ribs
[21]	Jeong, Kim and Koo, 2009	Longitudinal shear resistance of steel–concrete composite slabs with Perfobond shear connectors
[6]	Valente and Cruz, 2009	Experimental analysis of shear connection between steel and lightweight concrete
[22]	Vianna et al., 2009	Experimental assessment of Perfobond and T-Perfobond shear connectors' structural response
[23]	Ahn et al., 2011	Shear resistance of the Perfobond-rib shear connector depending on concrete strength and rib arrangement
[24]	Kim et al., 2011	Experimental and analytical investigations on the hat shaped shear connector in the steel-concrete composite flexural member
[18]	Papastergiou and Lebet, 2011	New steel-concrete connection for prefabricated composite bridges
[25]	Rodrigues and Laím, 2011	Behavior of Perfobond shear connectors at high temperatures
[11]	Kim et al., 2013	Experimental shear resistance evaluation of Y-type Perfobond rib shear connector
[26]	Wang, Li and Zhao, 2013	Ultimate Shear Resistance of Perfobond Rib Shear Connectors Based on a Modified Push-Out Test
[3]	Diógenes, El Debs and Valente, 2015	Experimental analysis of new interfaces for connections by adhesion, interlocking and friction
[27]	He et al., 2016	Experimental study on Perfobond strip connector in steel–concrete joints of hybrid bridges
[28]	Zheng et al., 2016	Parametric study on shear capacity of circular-hole and long-hole Perfobond shear connector
[29]	He, Fang and Mosallam, 2017	Push-Out tests for Perfobond strip connectors with UHPC grout in the joints of steel-concrete hybrid bridge girders
[30]	Wei, Xiao and Pei, 2017	Experiment study on fatigue performance of perforated shear connectors
[31]	Cho, Choi and Jeong, 2018	Direct and flexural shear strength of composite beam with Perfobond rib
[32]	Wang et al., 2018	Experimental research on PBL connectors considering the effects of concrete stress state and other connection parameters

2.2.1 Bibliometric analysis

The bibliometric indicators in the subject, can be useful, since it allows to measure indices of production and dissemination of knowledge, to follow the own development of the scientific discipline, as well as the standards of authorship, publication and use of research results.

Figure 5 shows the annual distribution of included studies, from 2002 to 2018. It can be seen that, in the first four years there were no publications, according to the exclusion criteria's in this SR, especially due to the absence journal publications until 2005 and the non-English language, once nowadays English is considered the global scientific language [33]. However, after 2009, there is an increasing trend in the number of publications, stabilizing from 2016.

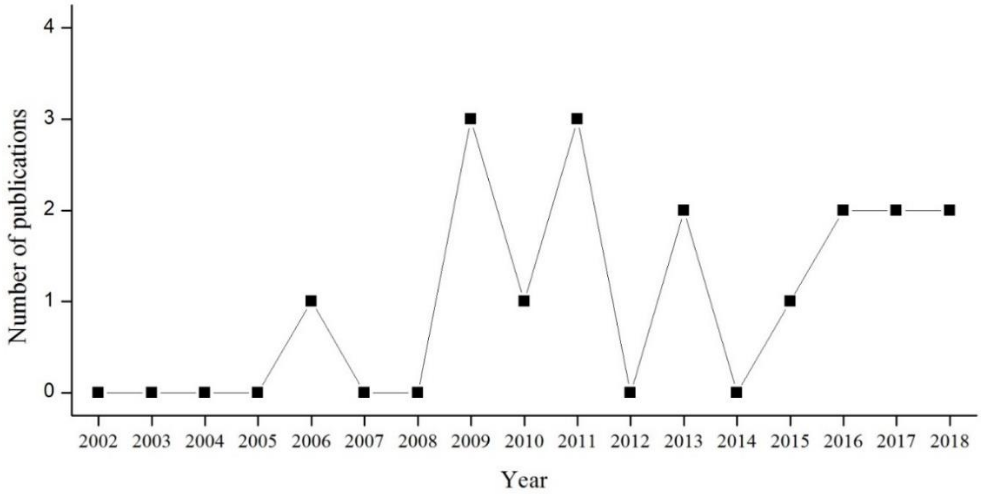


Figure 5. Annual distribution of publications, from 2002 to 2018.

About the journals and their attendance, regarding the publications of the studies are shown along with their SJR (SCImago Journal Rank) and IF (Impact factor) indicators for the last year. Both indicators make it possible to classify the performance and impact of scientific journals and are often used to classify them according to the relevance within its field.

Among these journals, as can be seen in Table 4, the Journal of Constructional Steel Research (JCSR) and Engineering Structures presented the highest indexes and can be seen as the most relevant journals in this field of knowledge. Another journal also presented high indexes as is the case of the Journal of Bridge Engineering, containing one publication.

Table 4. Journals covered.

Journal	**Quantity**	**SJR**	**IF**
Journal of Constructional Steel Research (JCSR)	9	1,892	2,509
International Journal of Steel Structures (IJSS)	2	0,590	0,734
Engineering Structures (ES)	2	1,690	2,755
Stahlbau (S)	1	0,247	0,321
Polymers & Polymer Composites (P&PC)	1	0,191	0,461
Advances in Structural Engineering (ASE)	1	0,599	0,968
Journal of Bridge Engineering (JBE)	1	1,081	1,454

From this perspective, 70% of the studies can be considered of high relevance, nine of them being published in the JCSR (Figure 6).

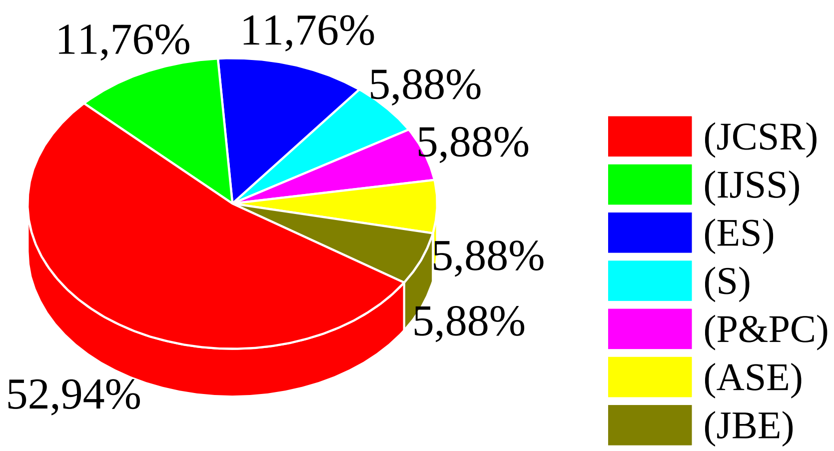


Figure 6. Frequency of journals.

Analyzing now the distribution citations through selected studies presented in Table 5, considering all the authors of each article, it is observed an expressive number of citation for the author Oguejiofor, E. C., with 34 citations followed by Maria Isabel B. Valente with 16 citations.

Table 5. Top 10 most cited authors.

Position	Qty of citations	Author
1st	34	Oguejiofor, E. C.
2nd	16	Valente, M. I. B.
3rd	13	Ahn, J. H.
	13	Veríssimo, G. S.
	13	Vianna, J. D.
4th	10	Kim, S. H.
5th	8	Kim, H. Y.
	8	Medberry, S. B.
6th	7	Leonhardt, F.
7th	6	Candido-Martins, J. P. S.
	6	Machacek, J.
	6	Su, Q. T.
8th	5	Al-Darzi, S. Y. K.
	5	Hegger, J.
9th	4	Hosaka, T.
	4	Veldanda, M. R.
10th	3	He, S. H.
	3	Kim, Y. H.
	3	Lebet, J-P.
	3	Neves, L. F. C.
	3	Ushijima, Y.

Table 6 presents the top 10 most cited references, distributed in alphabetical order among those with the same number of citations. According to the information contained in Table 5, two of the most relevant researches are by Ethelbert C. Oguejiofor, developed in the 1990s. Both researches were developed with Perfobond connectors, one with parametric study emphasis and the other in numerical analyzes of Push-Out models.

Another interesting fact is that two of the most cited studies, highlighted in Table 6, represented by the fourth and ninth positions, are part of the studies selected for this SR (See Table 3). This reflects the impact of these researches within the context addressed in this paper, as well as the relevant contribution to the technical state on Connections by Adherence.

Table 6. Top 10 most cited references.

Position	Qty of citations	Reference
1st	15	Oguejiofor, E. C., Hosain, M. U. (1994).
2nd	11	Oguejiofor, E. C., Hosain, M. U. (1997).
3rd	11	Valente, I., Cruz, P. J. (2004).
4th	6	Ahn, J.-H. et al. (2010).
5th	6	Cândido-Martins, J. P. S., Costa-Neves, L. F., Vellasco, P. C. G. da S. (2010).
6th	6	Machacek, J., Studnicka, J. (2002).
7th	5	Ahn, J.-H., Kim, S.-H., Jeong, Y.-J. (2008).
8th	5	Al-Darzi, S.Y.K., Chen, A.R. and Liu, Y.Q. (2007).
9th	5	Kim, H.-Y., & Jeong, Y.-J. (2006).
10th	5	Medberry, S.B. and Shahrooz, B.M. (2002).

2.2.2 Study characterization

Regarding the application focus of the composite connection, three different groups were found: bridge construction, building construction and general application. From the total, 53%, 12% and 35% of studies are in the first, second and third groups, respectively. It should be noted that, when the investigation focus is "general", some information may be valid for both, bridge and building constructions.

The tests for shear connectors in order to evaluate their structural behavior are standardized by Eurocode 4 [34]. The variables to be investigated include the geometry and the mechanical properties of the concrete slab, the type of shear connectors and the reinforcements. Considering these aspects, the test models present in the methodology of each study were analyzed.

At first, the model layout was analyzed in general terms and it was observed that eleven studies [6], [11], [20]–[23], [25], [28], [30]–[32], i.e. 65% of total adopted model similar to that presented in [34]. In addition six studies [3], [18], [24], [26], [27], [29], 35% of total adopted different setups in comparison to [34]. Overall, five different kinds of models were found as shown in Table 7.

Table 7. Overview of included studies.

Ref.	**Application**	**Push-Out test SETUP configuration**				
		Model type reference	**Concrete**	**Connector type**	**Interfaces**	**Slab type**
[20]	Bridge	Eurocode 4 [34]	Conventional	PBL	1, 2	Cast in-loco
[21]	Bridge	Eurocode 4 [34]	Conventional	PBL	1, 2	Cast in-loco
[6]	General	Eurocode 4 [34]	High Strength	PBL, Stud	1, 2	Cast in-loco
[22]	Building	Eurocode 4 [34]	Conventional	PBL, T-PBL	1, 2	Cast in-loco
[23]	Bridge	Eurocode 4 [34]	Conventional	PBL	1, 2	Cast in-loco
[24]	General	Matsui and Hiragi [35]	Conventional	PBL, Stud and Hat	1, 2	Cast in-loco
[18]	Bridge	Thomann [17]	High Strength	Adhe	3, 4, 5	Precast
[25]	General	Eurocode 4 [34]	Conventional	PBL	1, 2	Cast in-loco
[11]	Bridge	Eurocode 4 [34]	Conventional	PBL, Y-PBL	1, 2	Cast in-loco
[26]	General	Xia et al. [36]	Conventional	PBL	1, 2	Cast in-loco
[3]	Building	Thomann [17]	Conventional	PBL, Adhe	3, 4, 5	Precast
[27]	Bridge	Su et al. [37]	Conventional	PBL	1, 2	Cast in-loco
[28]	Bridge	Eurocode 4 [34]	High Strength	PBL	1, 2	Cast in-loco
[29]	General	Su et al. [37]	High Strength	PBL	1, 2	Cast in-loco
[30]	Bridge	Eurocode 4 [34]	Conventional	PBL	1, 2	Cast in-loco
[31]	Bridge	Eurocode 4 [34]	Conventional	PBL	1, 2	Cast in-loco
[32]	General	Eurocode 4 [34]	High Strength	PBL	1, 2	Cast in-loco

Notes:

PBL	Perfobond	1. Connector-Concrete
Stud	Stud	2. Flange-Concrete
Adhe	Connector by adherence	3. Connector-High Performance Mortar
T-PBL	T-Perfobond	4. Concrete- High Performance Mortar
Y-PBL	Y-Perfobond	5. Flange- High Performance Mortar

From the eleven studies that had a setup similar to the Eurocode 4 [34], a single study performed the tests with the standard Push-Out model [6]. This study aimed to evaluate the behavior of the shear connection in steel-concrete composite structures using lightweight concrete (LWC).

As a methodological strategy, all other studies presented some type of variation in the experimental setup, either referring to geometry, type and orientation of the load, connector type, etc. Rationally, the strategy adopted in the methodology is directly linked to the research objective. Therefore Table 8 presents the respective main variations of the experimental setup and its reasons.

Regarding the type of connector evaluated by the studies, about 94% - sixteen studies [3], [6], [11], [20]–[32] evaluated the Perfobond connector (PBL) which consists of a steel plate, with a limited number of holes, welded to the steel beam. In this sense, Perforbond is certainly the most used connector by adherence as object of study among researchers. Two studies evaluated a Connector by Adherence (Adhe) properly [3], [18]. This connector differs from the Perfobond mainly by the absence of the holes, where the resistance is provided by the adhesion, interlocking and friction at the interfaces.

In addition, other types of connectors were reported such as Stud, T-PBL (T-Perfobond), Y-PBL (Y-Perfobond) and Hat Connector, so that five studies presented comparative results and evidence [3], [6], [11], [22], [24] which: the first reported a comparative survey between Stud and PBL connectors; the second between PBL and T-PBL; the third between Stud, PBL and Hat; the fourth between PBL and Y-PBL; the fifth between PBL and Adhe (Table 7).

In order to simplify the comparison among the studies, the strength class of concrete has been divided in two groups according to [34]: Conventional and High Strength Concrete. The first group includes the concrete classes C20 to C50, while higher classes (> C55) are part of the second group. Thus, twelve studies [3], [11], [20]–[27], [30], [31] (65%) performed tests using conventional concrete, while five studies [6], [18], [28], [29], [32] (35%) used high-strength concrete (Table 7).

In addition to concrete, different materials were used to make the Push-Out models in order to characterize the adjacent region of the shear connector, i.e., the shear connection itself. Furthermore, it is known that, the connection structural behavior is, indeed, evaluated by the behavior of the interfaces formed by the materials which composes the connection

Therefore, it is important to mention that, only two of the studies [3], [18], reported a high performance mortar (HPM) to connect the parts involved in the connection. This fact is directly related to the investigation objective, evaluate the use of precast concrete slabs. On the other hand, the remaining studies perform Push-Out tests whose concrete was cast in place. Thus, the type of concrete structure and the interfaces evaluated in each study are too presented in Table 8.

Table 8. Main variations of the experimental setup of the Push-Out model and justification.

Ref.	Push-Out model	Main changes of layout	Justification
[20]	Eurocode 4 (1994)	Composite deck as structural system (Steel deck).	Aim to assess the usability of perfobond for composite bridge decks with profiled steel sheeting and application of the proposed deck system for a bridge.
[21]	Eurocode 4 (1994)	Composite deck as structural system (Steel deck).	Aim to assess the usability of perfobond for composite bridge decks with profiled steel sheeting and application of the proposed deck system for a bridge.
[6]	Eurocode 4 (1994)	No changes.	No reason.
[22]	Eurocode 4 (1994)	Thickness of slab.	To represent the thicknesses adopted in design practice for solid slabs in residential and commercial buildings structures.
[23]	Eurocode 4 (1994)	Dimensions of slab.	To determine the optimum perfobond-rib arrangement and to design a perfobond-rib shear connector for use in PSC-steel mixed girder systems.
[24]	Matsui and Hiragi (1988)	Horizontal setup, loading plate, single slab type.	To simulate more closely the behavior of concrete slab on I-shape steel girder.
[18]	Thomann (2005)	Two reinforced concrete blocks and a steel flange were the ribbed steel plates are welded. The gap between them filled with the high-strength cement grout.	To simulate the behavior of the new steel-concrete connection with prefabricated concrete slab.
[25]	Eurocode 4 (1994)	Vertical setup, single slab type.	To provide information concerning the general behavior and suitability for practical applications of Perfobond connectors in fire conditions.
[11]	Eurocode 4 (1994)	Dimensions of slab.	Aim to assess the behavioral characteristics of the newly proposed connector (Y-PBL).
[26]	Xia et al. (2009)	Horizontal setup, loading plate, dimensions of PRSC slab, dimension of connector.	In order to test PRSCs in the suspension bridge anchorages (Fourth Nanjing Yangtze River Bridge).
[3]	Thomann (2005)	As mentioned in Ref. [18]	To simulate the behavior of the new steel-concrete connection with prefabricated concrete slab.
[27]	Su et al.(2014)	Steel bearing plate connected directly with a PBL connector to transfer shear force between the concrete and steel plates	To simulate the performance of the PBL in the steel–concrete joints of hybrid girder bridges.
[28]	Eurocode 4 (1994)	Dimensions of slab.	Aim to assess the behavioral characteristics of the circular-hole and long-hole PBL connectors.
[29]	Su et al.(2014)	As mentioned in Ref. [27]	To simulate the performance of the PBL in the steel–concrete joints of hybrid girder bridges using UHPC grout.
[30]	Eurocode 4 (1994)	Dimensions of slab.	To investigate the fatigue behavior of perforated shear connection in steel-concrete composite bridges.
[31]	Eurocode 4 (1994)	Composite deck as structural system (Steel deck).	To investigate PBL shear connectors when are used as flexural materials in structures such as bridges.
[32]	Eurocode 4 (1994)	Dimensions of slab.	To investigate the transverse-force effect that arises from the use of prestressing tendons in the concrete roadway.

Another important parameter, variations in material composition (concrete and HPM) are essential for assessing the structural behavior of Push-Out specimens as they can directly interfere in parameters such as ultimate strength and cracking pattern. Then, as complementary information some characteristics were listed (Table 9) such as resistance range, density or presence of other components in the connection. It should be noted that the HPM material were purchased commercially and their composition was not presented in a specific way in [7].

All studies used conventional composition of the concrete (no additions), except for two studies [26], [29] where it was reported the use of reinforced concrete with steel fibers in their analyzes (Table 9). Only one study [6] evaluated the behavior of the connection under influence of lightweight concrete (LWC), while the remaining studies made use of concrete with normal density.

Other characteristics and methodological strategies are discussed here to support the discussion presented in the section (Table 9). The type of load and the method of application – displacement control or load control – used during the Push-out test is a determinant with regard to the type of analysis as such static or fatigue tests and the precision of the load-displacement curves obtained in all stages of test: pre-failure, failure and post-failure behavior. Eurocode 4 [34] presents guidelines related to the test protocol defining cyclic and monotonic steps of loading.

All studies evaluated the static structural behavior of the Push-out specimens and, complementary two studies also evaluated fatigue behavior [18], [30], where the first one opted for the displacement control method and the other by load control.

Table 9. Main characteristics of methodology.

Ref.	Nº of Specimens	Variations in Setup	Loading Type	DC / LC	Concrete Strength (MPa)	Density
[20]	4	Dimensions of composite deck.	Monotonic	DC	35.1 (a)	Normal
[21]	6	Presence of holes; Connector with holes and transverse reinforcement.	Monotonic	DC	30.0 (d)	Normal
[6]	9	Concrete strength; PBL and Stud; Number of holes in each connector; Reinforcement disposition and diameter.	Monotonic and cyclic	DC & LC	52.4 - 65.7	Low
[22]	12	PBL and T-PBL; Slab thickness; Number of holes in each connector.	Monotonic and cyclic	DC & LC	20.0 - 25.0 (d)	Normal
[23]	14	Concrete strength; Rib arrangement - Single and Twin PBL.	Monotonic	DC	27.4 - 52.6	Normal
[24]	9	PBL, Stud and Hat; Diameter of hole; End-bearing zone (Hat); Shape of transverse reinforcement (Straight or curved).	Monotonic	DC	24.0	Normal
[18]	12	No variation.	Monotonic and cyclic (Static and Fatigue tests)	DC	50.0 - 60.0 (d); 90.0 - 132.0 (e)	Normal Normal
[25]	32	Temperature (Room and High); Presence of transverse reinforcement and diameter.	Monotonic and cyclic	DC & LC	28.0 (a)	Normal
[11]	6	Concrete strength; Presence of transverse reinforcement; Angle of the Y-PBL; Thickness of rib.	Monotonic	DC	29.2 - 42.2	Normal
[26]	33	End-bearing zone; Thickness of rib; Tranverse reinforcement (presence and number).	Monotonic	LC	28.4 - 52.2	Normal (b)
[3]	12	Types of embossement (connector); Presence of holes; Presence of slab reinforcement.	Monotonic and cyclic	DC	38.7 - 54.4 (c) 75.9 - 87.2 (e)	Normal Normal
[27]	12	Bonding state (Interface PBL/concrete).	Monotonic and cyclic	DC	58.1 (a)	Normal
[28]	21	Hole diameter; Hole length; Hole heigtht.	Monotonic and cyclic	DC & LC	70.3 (a)	Normal
[29]	24	Bonding state (Interface PBL/concrete); Presence of holes; Presence of transverse reinforcement (by the hole in plate); Volume of steel fibers.	Monotonic	DC & LC	115.5 - 124.7	Normal (b)
[30]	24	Hole diameter; Presence of transverse reinforcement and diameter; Thickness of rib.	Monotonic and cyclic (Static and Fatigue tests)	LC	50.0	Normal
[31]	5	Number of holes in each connector; Distance of holes; Presence of the transverse reinforcement.	Monotonic	NI	31.0 (a)	Normal
[32]	33	Presence of prestressing reinforcement; Stress state of the surrounding concrete (Tensile and compressive stresses); Diameter of hole; Diameter of transverse reinforcement; Thickness of rib.	Monotonic	LC	56.0	Normal

Notes: (a) Mean value; (b) Steel fiber; (c) Prismatic; (d) Design strength; (e) HPM strength; DC - Displacement control; LC - Load control; NI - Not informed.

Five studies that evaluated only static behavior, chose to use both, displacement and load control [6], [22], [25], [28], [29], while only three studies opted only the load control methodology [26], [30], [32] and one study has not informed the methodology [31].

In each study, attention was given to the strategic plan adopted in each methodology regarding the variation of the characteristics of the models, as mentioned previously. Nevertheless, Table 9 addresses more specifically these strategic details of the respective experimental programs.

2.2.3 Discussion

2.2.3.1 Load capacity

In order to discuss the shear resistance capacity of the linear connectors, a quantitative analysis was performed. Thus, this comparison is made with the maximum load value obtained by the linear connector and expressed in terms of load per meter. This parameter can be obtained by dividing the specimen maximum load capacity by the total length of the connector. It should be noted that was not possible to collect sufficient data in Kim [20] for the analyzes in this topic.

In this sense, it is emphasized that the data collected for this discussion consider only the connector by adherence and Perfobond connectors (Non-twin Perfobond).
Still, considering the wide range of methodological variables present in the studies, simple averages of the respective ultimate shear resistance data of the composite connection were performed in order to simplify the discussions, disregarding, for example, whether there is presence or not of concrete end-bearing zone, presence of transverse reinforcement bar, the thickness of the connector, etc.

Figure 7 shows the connector load capacity values for each study included in this systematic review. To support the analysis, reference values are included, which refer to the load capacity per meter of Stud connectors. The load values for studs were obtained considering the minimum and maximum spacing according to Eurocode 4 [34] recommendations. For the calculation, the HEB 260 steel profile referring to the Push-out test was considered.

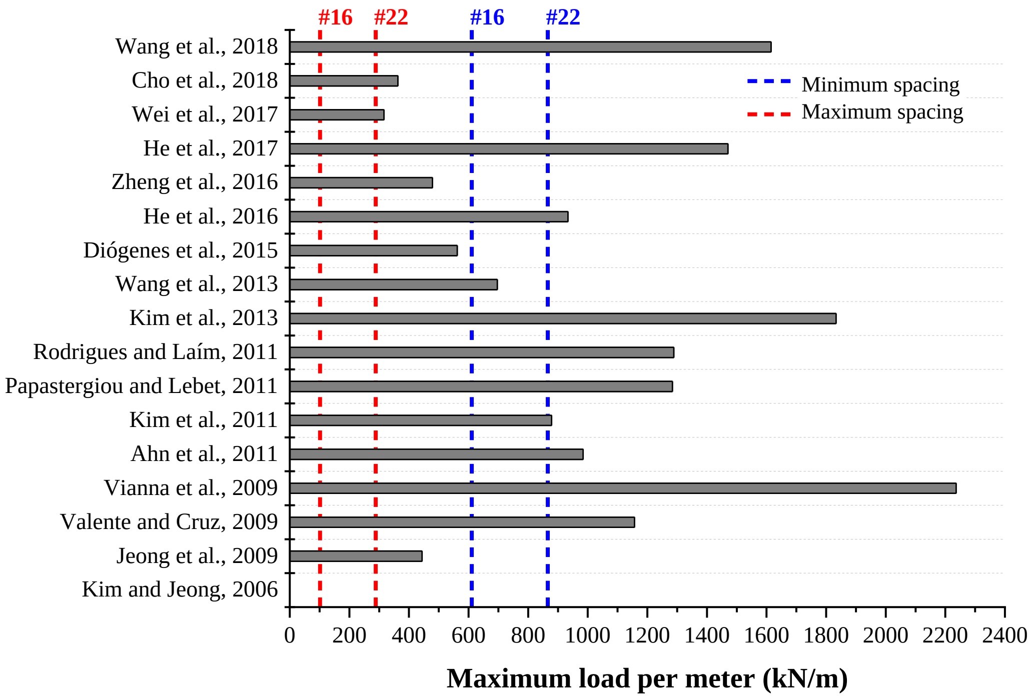


Figure 7. Connector – Load per meter.

According to Figure 7, it is clear that two stud connectors with different diameters were considered, one with 16 mm and one with 22 mm, in order to try to idealize their applications in small and medium / large size residential buildings construction, respectively.

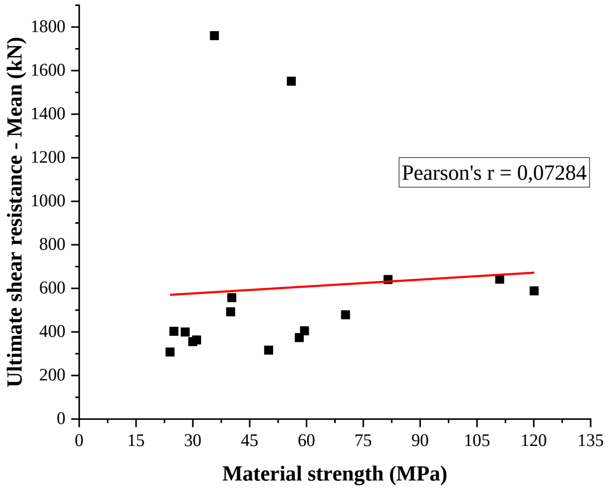
It can be noted from Figure 7 that in 10 cases the shear resistance of the linear connector is greater than the resistance obtained by the 22 mm diameter Stud (#22) considering the minimum spacing between them. Of these, only the work by Vianna [22] already presented discussions about the application of the linear connector in building construction, but not in terms of resistance per meter of the connector.

From this perspective, this represents that about 60% of the tested linear connectors are certainly liable to low and medium size residential applications, where the stress level is lower than that of bridge structures, for example, as reported the others studies (See Table 7).

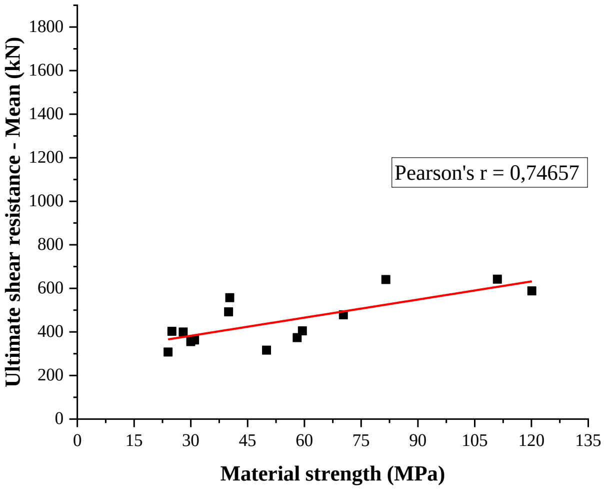
Considering the maximum spacing between Stud connectors, all cases presented satisfactory results, which may indicate the efficient application of these connectors in building structures with lower stress solicitation. Accordingly, it should be considered that in order to achieve the same load capacity obtained with the linear connector, in most cases a high number of Stud connectors per meter is required [3].

A second quantitative analysis was performed in terms of the Ultimate Shear Resistance average (USR) of the composite connection consisting of linear connectors. The objective was to measure the relationship the USR has with two other variables: Material Strength at the interface with the connector and Connector Thickness, measured by Pearson's correlation coefficient (r).

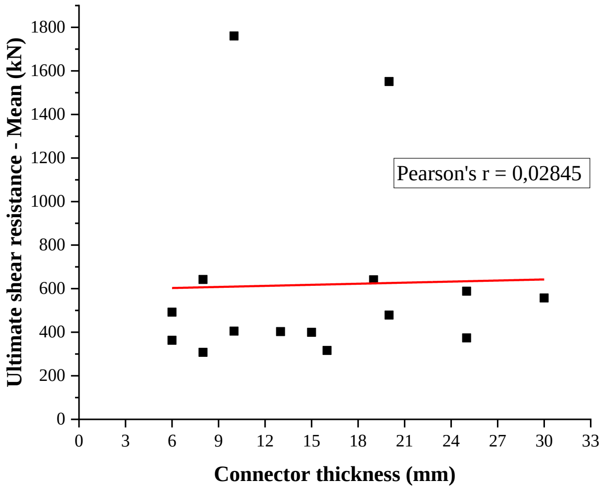
Figure 8.a to Figure 8.d show the respective scatter plots. From a quick inspection it is important to note that there are Y-axis outliers regarding the USR obtained in the work of Kim et al. [11] Wang et al. [32]. These values tend to distort and underestimate the relationship of USR of the composite connection between the variables mentioned. Therefore, can observe the difference in the results of the correlations between the variables considering or not these outliers.



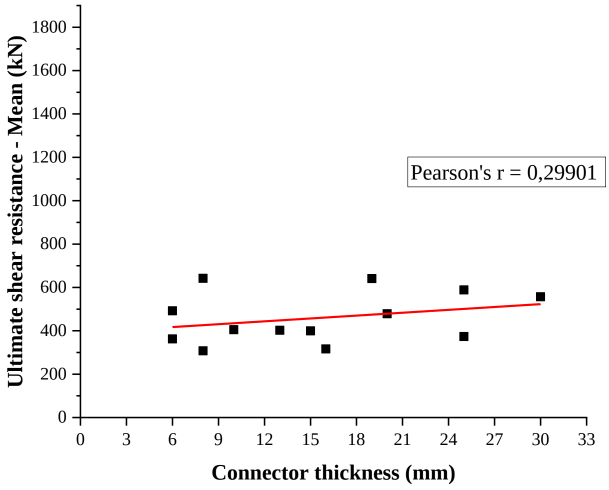
(a)



(b)



(c)



(d)

Figure 8. Correlations with USR.

According to Figure 8.a and Figure 8.c, which considered the presence of outliers, suggests that there would be no association between the variables, either due to the Material Strength at the connector interface or the Connector Thickness, with Pearson's r equal to 0.07284 and 0.02845, respectively.

After the elimination of outliers, in the case of Material Strength, a positive relationship with moderate to strong degree of association of this parameter with USR is considered, with Pearson's r 0.74657 (Figure 8.b). That is, certainly these variables are statistically dependent. In this context, Ahn [23] and Kim et al. [11] point to the evidence that the USR is proportional to concrete strength, where it increases dowel and end-bearing strength.

In the second case, regarding Connector Thickness, a positive relationship is also observed, but with a weak to moderate degree of association between the variables, and the Pearson's r correlation coefficient is 0.29901 (Figure 8.d), which infers the dependence between the variables in question.

However, a series of categorical factors make it impossible, a priori, to affirm the causality between the variables analyzed here, as they also influence the magnitude of the USR of the connection, such as: the presence and geometric characteristics of holes in the connector [3], [21], [27]–[32]; the presence of transverse reinforcement [11], [25], [26], [29]–[31]; the presence of concrete end-bearing zone - directly associated with Connector Thickness [24], [26].

Nevertheless, it is inferred that the use of these linear shear connectors in steel concrete composite structures in the construction of buildings is satisfactory, given the high shear strength presented.

2.2.3.2 Ductility

To compare the ductility of the connector based on the push-out results in Eurocode-4, the characteristic load denoted by P_{rk} is defined as the ultimate load (P_u) reduced by 10% and the characteristic relative slip, denoted by δ_{uk}, as shown in Figure 9. For shear connectors, Eurocode 4 [34] recommends a characteristic value of plastic deformation of at least 6 mm in order to characterize it as ductile.

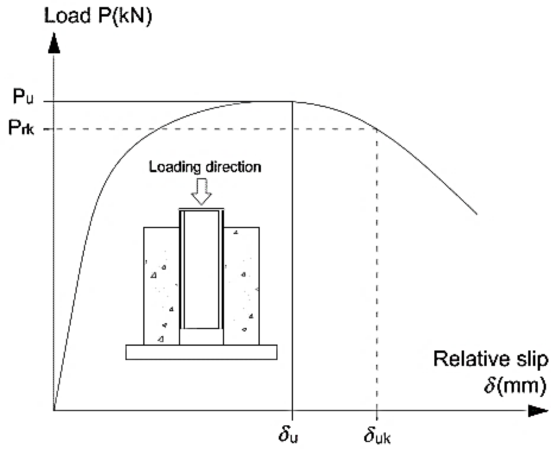


Figure 9. Definition of characteristic slip [23].

According to the studies included in this review, data regarding the characteristic slip of linear connectors were extracted. Figure 10 shows the average values obtained under normal temperature conditions and considering only the linear adhesion and single Perfobond connectors. It should be noted that some research did not provide the exact data needed for the analysis, thus the values represented in green were estimated as a function of the Load *x* Slip graphs contained in the respective works. In addition, in Kim et al. [24] not provided enough information.

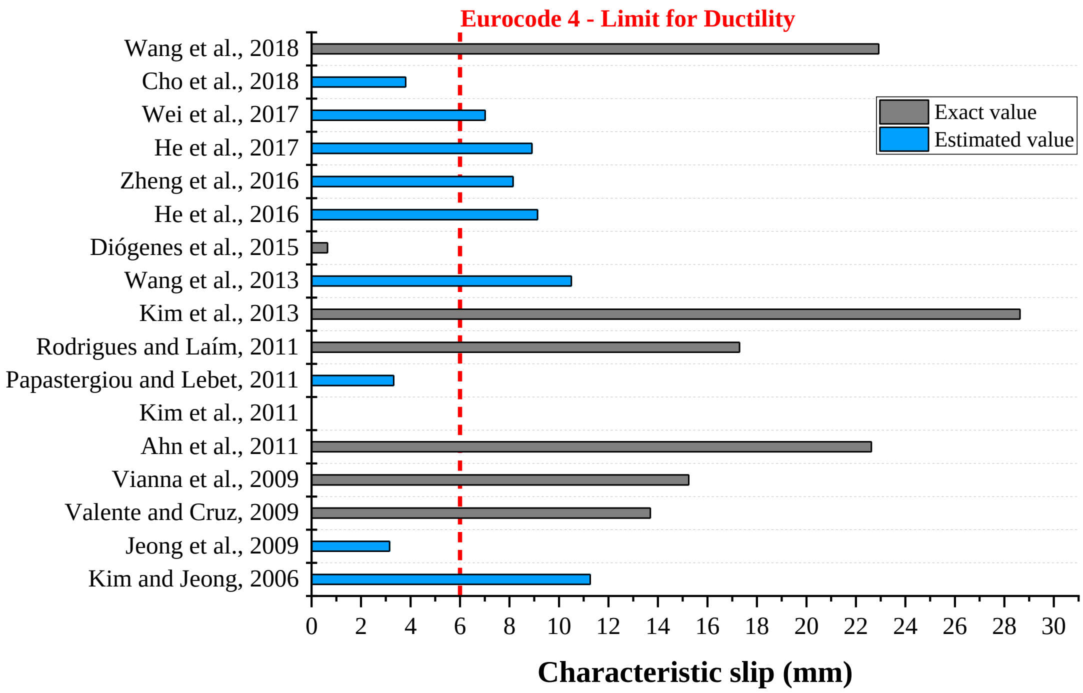


Figure 10. Characteristics slip of studies.

According to Figure 10 it is possible to see a limit reference ruler for the ductility rating of the connectors. Then, it is noticed that 12 works presented connections with ductile characteristics, i.e., they present high load capacity even with high deformation. This represents about 70% of the studies.

On the other hand, it was concluded that 4 papers presented non-ductile connections. Of these, we highlight the research by Papastergiou [18] and Diogenes et al. [3] who tested Push-out specimens for the precast structure using 3 shear interfaces. Thus, the material present at the interface with the connector is a high performance mortar (HPM), a factor that certainly stiffened the composite connection. That is, half of the researches that showed fragile connections have this characteristic. However, the connection exhibits high stiffness, sufficient static and fatigue resistance, and adequate deformation capacity, allowing the formation and design of ductile composite structural elements [18].

Furthermore, Ahn [23] from his work states that the Perfobond-type linear connectors have sufficient shear capacity and ductility, and can be used in composite structures in general. Importantly, under fire conditions the mechanical characteristics of the connections made with these connectors change, which implies a reduction in their ductility [25].

In general terms, it is understood that linear connectors certainly apply efficiently in building construction if considered the ductile behavior presented in most cases. Ductility is defined as the ability of the structural system to experience inelastic deformations without losing its resilient capacity, reaching rupture after considerable accumulation of inelastic deformation energy. Therefore, it is a desirable condition for composite structure behavior, especially in seismic countries.

2.2.3.3 Cracking patterns and failure mode

It is important to identify the failure modes and cracking patterns that may occur in Push-out tests in order to analyze the structural behavior of the specimen. Specimen rupture, whether fragile or ductile, is mainly due to slip development. This behavior is a result of the shear stresses that are generated with the load and can develop between each of the elements that compose the shear interfaces. However, when the model presents more ductility, it is possible to better evidence the ruptures in the interfaces [3]. Another important advantage is that the interface rupture criteria are fundamental to create analytical models for calculating connection resistances [18].

According to the review studies, the main failures can be conditioned by connector failure, the concrete slab cracking, by crushing failure of the concrete dowel, and by shear failure of the transverse reinforcement (Table 10). Wang [32] states that if any of these loading-carrying components is severely compromised, the full shear capacity of the connector cannot be realized. However, the main limitation to the strength of the connection and consequently to the rupture of the model is the rupture of the concrete slab. Having said that, it is of interest to make the following points:

- Eight studies presented as their main mode of rupture of Push-out models the rupture of concrete slabs, which represents almost 50% of cases. Usually the main cracks occur in the external region of the slab in the longitudinal direction [3], [6], [11], [20]–[23], [26].
- From evidence presented by Vianna [22] and Wang [32] the rupture governed by the connector rupture is usually associated with another mode of rupture. It is important to note that this type of failure (by the connector failure) was recorded in only 11% of the works, which characterizes a mechanical stability of the connector against the imposed stress level. In these cases, the shear planes are formed without damaging the other

components of the connection [26].

- Fragile ruptures are usually seen in models that do not have transverse reinforcement, as seen in Valente [6]. These retard standard cracks in the common regions (longitudinal direction on the slab face); It should be noted that, in addition to preventing cracking due to tensile stresses in the connector region, the transverse reinforcement contribute significantly to increase the confinement in that region, which is desirable in connections by adhesion, interlocking and friction [3]. However, when there are prestressing effects on the slab, the tendency is to deform the transverse reinforcement severely and to rupture the concrete dowels. Wang [32] explains that the reasons for this "can be attributed to the confinement effect provided to the concrete by the prestressed lateral tendons and to the increased friction at the steel-concrete interface. Confinement tends to increase strength and stiffness of concrete, retard cracking and allow the concrete dowel, connector and crossbars to develop their full strength".
- Four studies did not provide information and / or evidence on the type of failure mode.

Table 10. Main failure mode.

Ref.	**Main failure mode**
1	Concrete slab cracking.
2	Not informed.
3	Concrete slab cracking.
4	Connector failure.
5	Concrete slab cracking.
6	Not informed.
7	Not informed.
8	Concrete slab cracking; Steel profile.
9	Failure of the concrete dowel; Failure of transverse reinforcement.
10	Failure of transverse reinforcement.
11	Concrete slab cracking.
12	Failure of transverse reinforcement.
13	Concrete slab cracking.
14	Failure of the concrete dowel.
15	Failure of the concrete dowel; Concrete slab cracking; Failure of transverse reinforcement.
16	Not informed.
17	Concrete slab cracking; Connector failure; Failure of transverse reinforcement; Concrete dowel failure.

Therefore, it is understood that the composite connection from linear connectors has its limit of rupture usually governed by the rupture of concrete slabs and transverse reinforcement bars, which indicates that the linear connectors have sufficient stability and stiffness in face of their use in steel-concrete composite structures in general.

2.3 Conclusions

In this study, a systematic review was performed in order to propose a new discussion about the continuous shear connectors about its application in composite steel-concrete structures, mainly in building construction. For this, a bibliometric analysis of the studies was performed in order to identify the main ideas of application of the connectors, as well as the methodological strategies used by the respective authors. In addition, a quantitative analysis was made on the shear strength and ductility of the respective connectors, which are the main parameters to evaluate their structural behavior. Further, it was qualitatively discussed about the main rupture modes of the composite connection. Thus, it can be concluded that:

- The synthesis of the wide range of studies and their respective methodologies allowed a new way of thinking about linear connectors and their application. In this context, the connectors present sufficient shear resistance and ductility so that it can be applied to several types of composite structures, mainly in buildings construction;
- Material strength at the interface from linear connector is strongly associated with the ultimate shear resistance (USR) of the composite connection. In this case, it is important to emphasize that the main limiting factor for the rupture of Push-out specimens is the failure of the concrete slabs. However, the USR of the connection is associated with categorical parameters such as the presence of the transverse reinforcement and the concrete end-bearing zone, which makes the more careful analysis of the results difficult.
- Connector Thickness is a minor factor in the ultimate strength magnitude of the composite connection unless concrete end-bearing zone is present.
- The presence of transverse reinforcement usually provides greater ductility to the composite connection, as well as mitigating the propagation of cracks in the concrete slab, which are characteristics desired for steel-concrete composite structures.

CHAPTER 3

EXPERIMENTAL PROGRAM

The next sections will describe the push-out tests performed in the LABEME – Laboratory of Tests in Materials and Structures at the Federal University of Paraiba, Brazil.

The Push-out tests allowed to study the interfaces involved in the proposed connection by adherence, identifying the order of magnitude of the resistances and the failure modes. For this, were obtained the experimental prototype responses in terms of the load *x* slip behavior, which can provide a criterion of connection rupture, and the slab uplift *x* slip behavior, which can translate a kinematics law that would describe the prototype deformed configuration.

3.1 Methodology

In this research will be evaluated experimentally only one type of linear connector by adherence with ribbed surface originating from the checkered steel plate, which is commercially disseminated in Brazil, aiming to produce efficient connections by adherence and, at the same time, adapt the technology to the Brazilian construction market. Also, it was intended to evaluate the use of this connector specifically on prefabricated slabs of the lattice type, characterizing the initial hypothesis of the work.

It is a type of precast slab that has a prefabricated lattice joist as rib reinforcement, attached to a concrete slab. In the gaps between this structure, some inert material is used, such as expanded polystyrene (EPS) or ceramic blocks.

However, it was decided to complete the whole model at a single time with the objective of eliminating a possible problem caused by the presence of a cold joint, since there would initially be concrete with different resistances in the same specimen. Then, the trusses were used as reinforcement in the ribs and the slabs were cast in loco in whole. Thus, in this research the slab is denominated and classified as a ribbed slab.

3.2 Specimen description

Six prototypes were manufactured, based on the recommendations of Eurocode 4 [34], to carry out the Push-out tests. These consist of a steel beam, by means of a continuous rib steel connector, to two identical reinforced concrete slabs. The connector is welded longitudinally on the flange of the steel beam which is embedded in the concrete slab after concreting to ensure the connection between them.

In order to enable new discussions on Connection by Adherence, two different Push-out specimens were designed. The distinction of the specimens refers to the type of slab, i.e., there is no variation in geometry or physical properties of the linear connector and the steel-based profile. Therefore, changes in the slab type allowed evaluate the behavior of the connection proposed with different dispositions and inertia providing a comparative perspective of experimental results between specimens. Thus, three specimens use solid reinforced concrete slabs named MAC-1, MAC-2 and MAC-3, and three other models use ribbed slabs named TREL-1, TREL-2 and TREL-3.

In order to obtain the same roughness on the two faces of the connector, two identical parts are welded on their smooth faces, producing the ribbed connector on both sides. This ensures the symmetry of the model and the similarity of features in the connector-concrete surface for shear resistance and transverse separation between the concrete slab and the steel-based profile (uplift).

Whereas each checkered steel plate that composes the linear connector is 4.75 mm (3/16") thick, the total thickness of the connector is 9.5 mm. The total length and height are 550 mm and 50 mm, respectively. It should be noted that the surface of the plate has ribs of 1 mm in 45° equally spaced and intercalated as a function of the direction as seen in Figure 11.a. This roughness present in the connector serves to provide the transfer of shear between the involved interfaces.

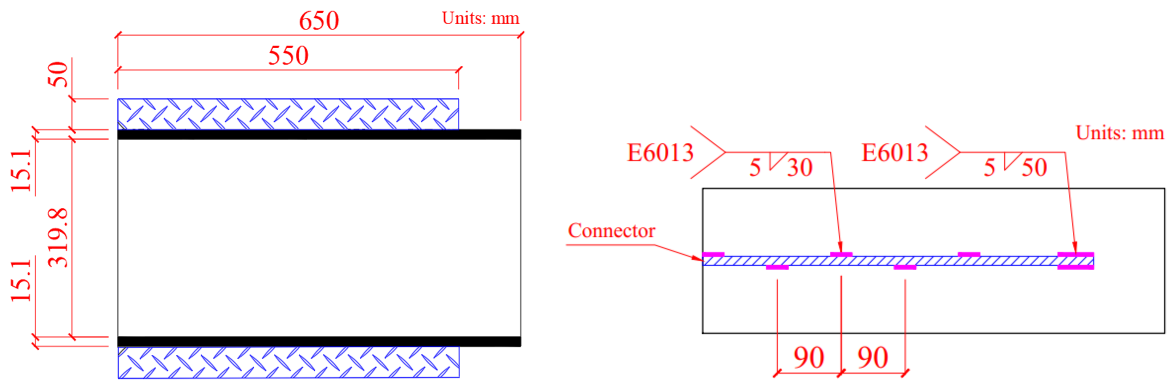


Figure 11.View of Connector + Steel-based profile.

Concerning to the steel-based profile, the one used in the present research corresponds to the W360 x 72 (ASTM-A572 grade 50). This steel profile presents characteristics similar presented in Eurocode 4 [34]. It should be noted that the availability of the profile in the supplier companies of the region where the research was developed was also a determining factor for this choice. The profile used in each model has a total length of 650 mm, where the connector already welded to the steel-based profile can be seen in Figure 3.

The first type of slab is a plane reinforced concrete slab, where the rate and arrangement of the reinforcements were based on Eurocode 4 [34], as shown in Figure 12.a. The second type of slab, Figure 12.b., is a ribbed slab similar to a precast ribbed slab made by lattice joist, very common in constructions of small buildings in Brazil.

The reinforcement arrangement differs according to the typology of the slabs, as shown in Figure 12. In the plane reinforced concrete slab, the reinforcements were arranged in a similar way to that presented in Eurocode 4 [34]. Steel CA-50 bars of 8 mm diameter were used in all positions equally spaced.

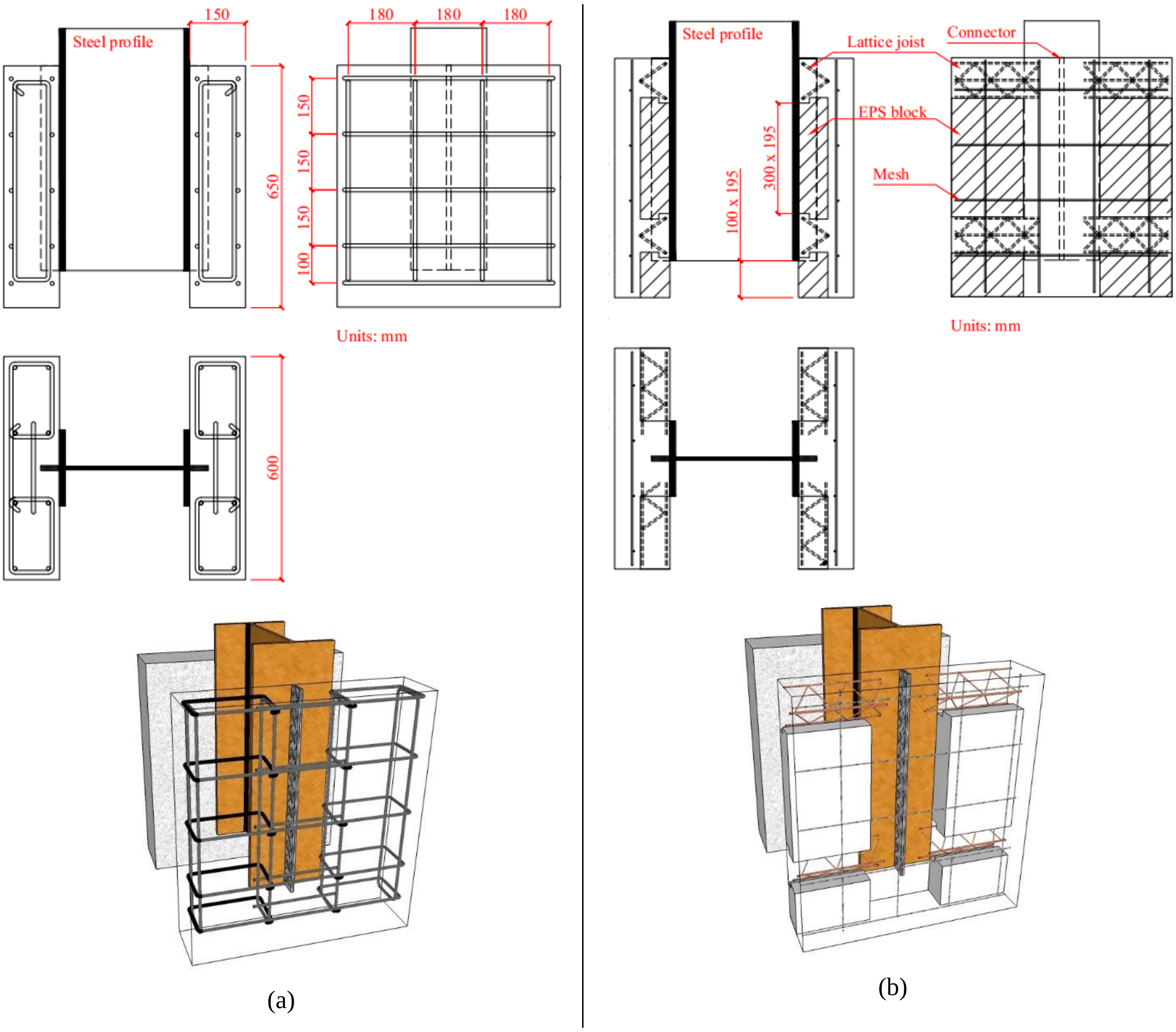
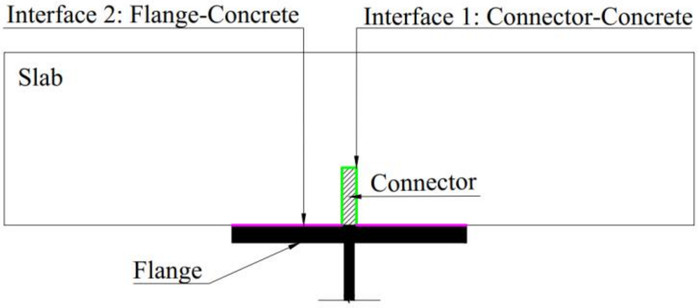


Figure 12. Specimens (a) MAC; (b) TREL.

About the ribbed slab, the reinforcements consist of TG8SL – GERDAU® trusses with 8 cm of height, made by steel bars of 6.0 mm, 3.4 mm and 4.2 mm of diameter in the top flange, diagonally and bottom flange, respectively. In addition, an electro-welded mesh produced with CA-60 steel bars of 3.4 mm diameter and equally spaced in both directions each 15 cm was used. This mesh is commonly used to prevent excessive cracking due the concrete shrinking.

Also, previously the tests, the specimens MAC-1 and MAC-3 were submitted to intentional deteriorations, Figure 13.a, in the inner region of both slabs below the steel based profile, in order to avoid no predicted parcels of resistance i.e. ensure that the bond strength is given only by the interfaces (Figure 13.b). More specifically, avoid that the strength portion provided by the end-bearing concrete zone is not influenced by the steel profile, but only by the connector.

(a)



(b)

Figure 13. (a) intentional deteriorations detail; (b) Interfaces – legend

3.3 Material properties

For the concrete, the compressive strength and elasticity modulus were obtained from cylindrical samples, using the recommendations of [38] and [39]. It should be noted that, for the determination of the modulus of elasticity of the concrete, nondestructive tests were carried out using the Sonelastic® software [40]. Finally, the tensile strength of the steel profile and connectors was referenced to ASTM A36 and A572 grade 50, respectively. Table 11 summarizes the mechanical properties of all the materials used in the connection.

Table 11. Material Properties

Specimen	**$E_{long,din}$ (GPa)**	**f_{cm} (MPa)**
MAC-1	32.00	27.89
MAC-2	31.05	29.78
MAC-3	30.11	33.85
TREL-1	33.98	33.84
TREL-2	32.23	32.34
TREL-3	32.04	24.71
	31.90 ± 4.06% *	30.40 ±12.0% *
Steel	**Tensile Strength, Ultimate (MPa)**	
Beam	450	
Connector	400-550	

*Average and RSD, respectively.

3.4 Test setup and loading procedures

According to Eurocode [34], monotonic and cyclic tests were carried out aiming to evaluate the ultimate strength of the connection and obtain the complete load-slip curve and to analyze the relation between uplift and slip.

The test was divided into four distinct phases in order to be able to effectively evaluate the behavior of the specimen [34]. Phase 1 consists of a pre-load of 20 kN. Phase 2 is characterized by the cyclic loading, where 25 cycles of loading and ranging from 20 kN to 100 kN are applied at a speed of 1 kN/s. At the end of the cyclic loading, Phase 3 is started, characterized as reload situation, where the load increases from 20 kN to 100 kN at the same speed, approximately 1.0 kN/s. To conclude, Phase 4 of the test is characterized by the continue load, at a rate of 0.5 kN/s. Figure 14 summarizes the load sequence.

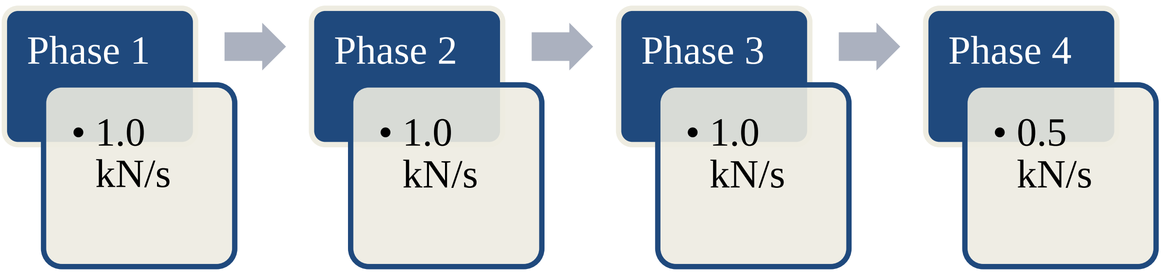


Figure 14. Load steps

Six dial indicators (LCD) were used for the monitoring of the test, two of these with a maximum range of 101.6 mm (4 ") and four with a maximum range of 25.4 mm (1"). In addition, a resistive displacement transducer (LVDT) with a maximum range of 25.4 mm (1") was used. The instrumentation used in the performed push-out tests is presented in Figure 15.

The LCD-1, LCD-2, LCD-4 and LCD-5 indicators have been installed to measure the relative slips between the block and the connector. For this, they were positioned at half height of the model. As seen in Figure 15, each slab has two LCD's in order to present average slip results. The LCD-3 and LCD-6 indicators were positioned between the two slabs in the upper region to measure the relative transverse displacement between them – uplift. It is important to note that these two devices had the same slab as a reference base. The LVDT, in turn, was used as a relative slip control device located directly on one of the connectors.

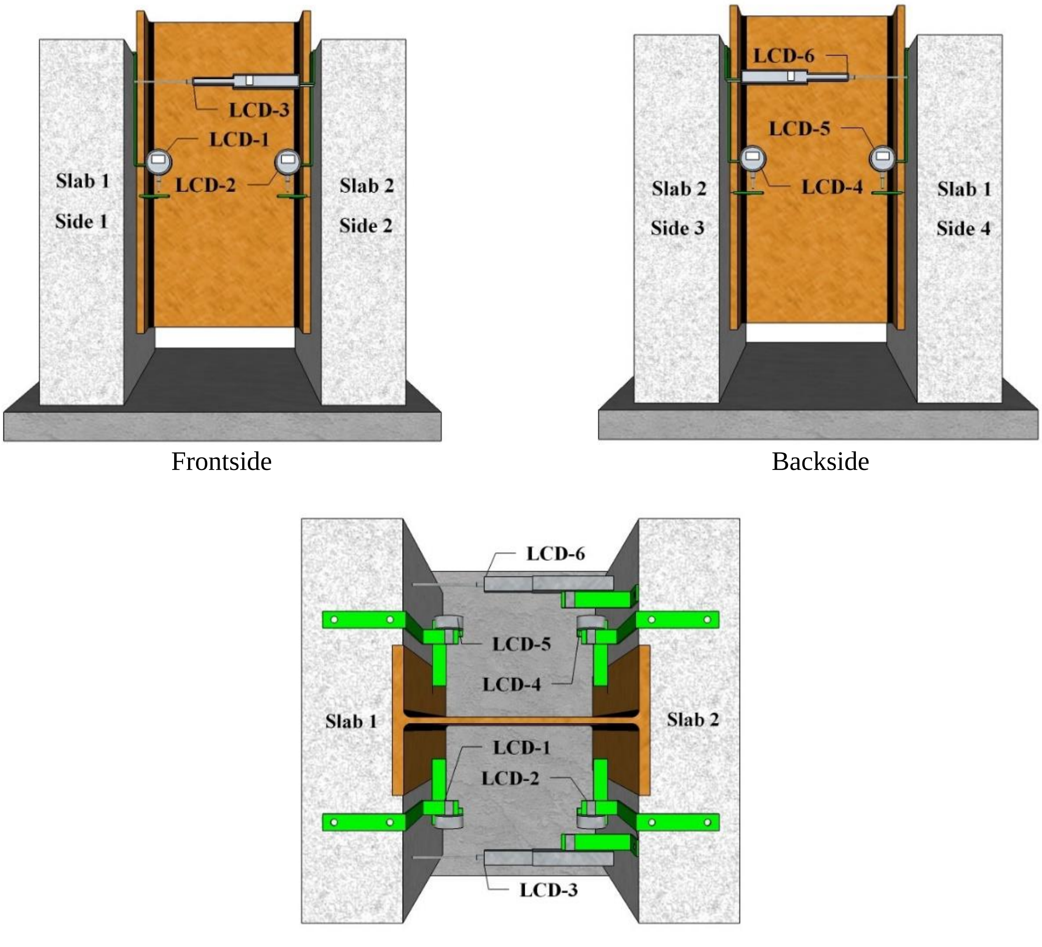


Figure 15. Instrumentation setup

3.5 Results and discussion

3.5.1 Maximun load capacity

Table 12 presents the results obtained from the push-out tests carried out on all specimens. The compressive strength of the concrete (f_c) in MPa is presented individually; the maximum load (P_{max}) in kN; the slip referring to the maximum force (δ_{Pmax}), in mm; the characteristic load corresponding to 90% of the maximum force (P_{rk}), in kN; and the characteristic slip (δ_{uk}), in mm. The slip values presented in Table 12 are the average of records obtained in the LCD-1, LCD-2, LCD-4 and LCD-5.

In terms of maximum strength, the specimens that used plane reinforcement slabs (MAC specimens) presented higher value on average and lower variation when compared to the ribbed slab (TREL specimens). MAC specimens reached, on average, a maximum strength of

394.40 kN with RSD of 7.99% while the TREL specimens reached 346.06 kN with RSD of 20.04%. Thus, it should be noted that the maximum strength of the TREL specimens reached about 87% of the reached by the MAC specimens.

Table 12. Main results obtained in push-out tests.

Specimen	f_c (MPa)	$P_{máx}$ (kN)	$\delta,P_{máx}$ (mm)	P_{rk} (kN)	δ_{uk} (mm)
MAC-01	27.89	359.10	2.02	323.19	5.47
MAC-02	29.78	419.80	4.05	377.82	8.12
MAC-03	33.85	404.30	2.57	363.87	8.41
		394.40 ± 7.99% *			
TREL-01	33.84	409.20	2.40	368.28	7.00
TREL-02	32.34	357.20	2.89	321.48	4.01
TREL-03	24.71	271.80	1.86	244.62	3.94
		346.06 ± 20.04% *			

*Average and RSD, respectively.

The TREL-3 model presented a maximum load capacity of only 271.80 kN, considered atypical when compared to all other specimens whose values of maximum strength is between 357.20 kN and 419.80 kN, considering the MAC and TREL specimens. This phenomenon may be explained by the asymmetrical behavior of the model during the test, which resulted in the rupture model side while the other remained almost intact, thus compromising the specimen maximum strength (See Figure 20.f). The asymmetry is mainly associated with failures in the design of forms and concrete, which may have led to undesired eccentricities.

In terms of slip presented at the maximum load, the MAC specimens presented an average value of 2.88 mm while the another specimens presented 2.38 mm. Unexpectedly, the models with higher resistance obtained also higher slip, since the maximum load increase is usually associated with the lower slippage capacity, as presented in other studies, such as [3], [4], [10].

Figure 16 shows the behavior of the specimens tested in terms of Load *x* Slip. Figure 16.a refers to the evolution of the relationship between the parameters throughout the test, while Figure 16.b represents a “window” where the models reach the maximum load capacity.

According to results, it is remarking the stable and similar behavior between the MAC type specimens, whereas the TREL specimens do not present the same similarity. Certainly, the asymmetrical behavior observed in the TREL specimens explains this difference. An analysis of the failure modes is presented in item 3.5.2.

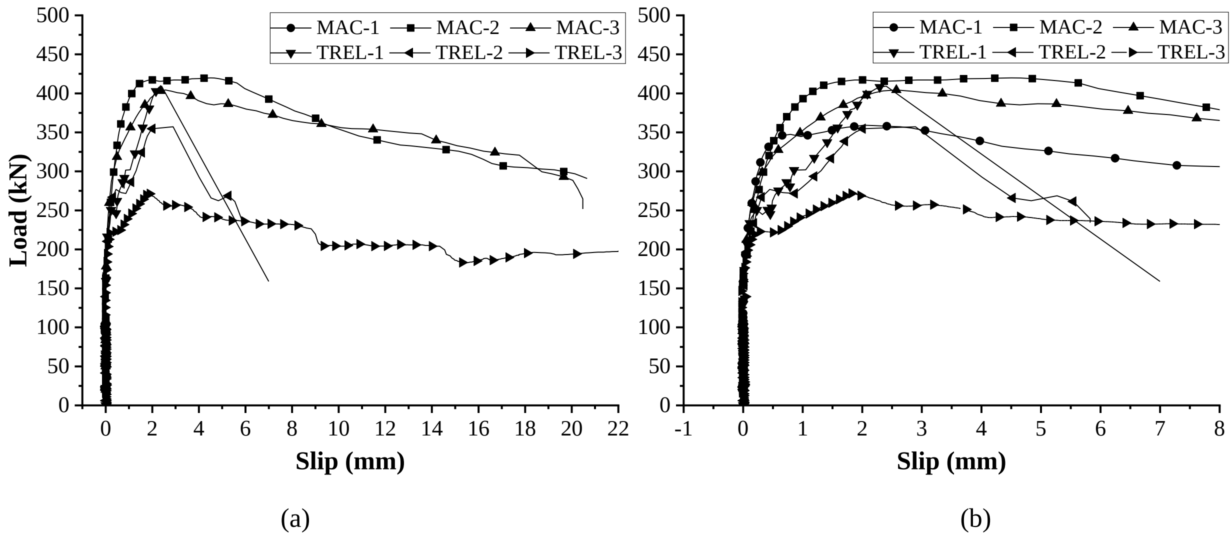


Figure 16. Results – Load *x* Slip.

Related to MAC specimens, these, showed a gradual and continuous deformation, increasing from the instant of the maximum load until the end of the test, except for the MAC-01, which presented some residual stiffness, in which it reacquired load capacity from 11 mm of slip. This result probably, must be related to the activation of resistant mechanisms related to the presence of reinforcement in the slab. According to [3], the reinforcement in the slab increases the confining stresses on the connector, which, in some way, may have contributed to the occurrence. Other factors as friction in Interface 1, as well as the interlocking effect may have contributed to the occurrence too.

3.5.2 Failure modes

Complementary the presentation of main results, it is important to identify the failure modes that can possibly occur on the test in question. As can be seen in Figure 13.b there are two interfaces involved in the Connection by Adherence proposed: Interface 01 — between concrete and connector, Interface 02 — between the concrete and flange.

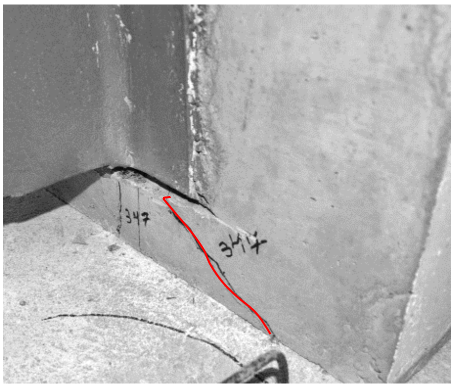
The mechanism of rupture of these interfaces is basically due to the relative slip, which generates normal stresses at the connector surface that imply the rupture of the concrete slab.

For this reason, another phenomenon can be identified, the uplift, characterized by the transverse displacement of the interfaces. The combined effect of slip with uplift results the deformed of the model. It should be noted that, the slip results from the shear stresses that are generated with loading. Thus, all modes of rupture occur due to the slip. However, does not mean that, the failure of Connection by Adherence occurs with the beginning of slip.

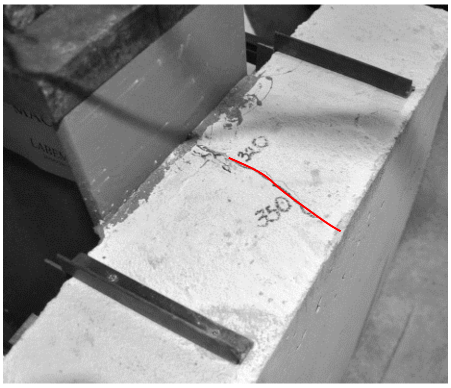
3.5.2.1 MAC specimens

In the MAC-01 specimen, the presence of the first cracks in the region near the connector at the top of slab 2 was observed, around 331.40 kN of loading. This load already represents 92% of maximum strength of specimen. New cracks appeared on the inner side of slab 2, at the zone immediately below the connector, for a load of 347 kN.

The MAC-01 reach a maximum load of 359.10 kN, recorded after 46 minutes of test where it was possible to observe more significant openings of existing cracks, especially in the inner region of slab 2 (Figure 17.a). In this region was recorded the beginning of the cracking of the concrete, which indicated the rupture of the slab and, consequently, the failure of the specimen. Cracks began to appear in the connector region at the top of the slab 1 (Figure 17.b).

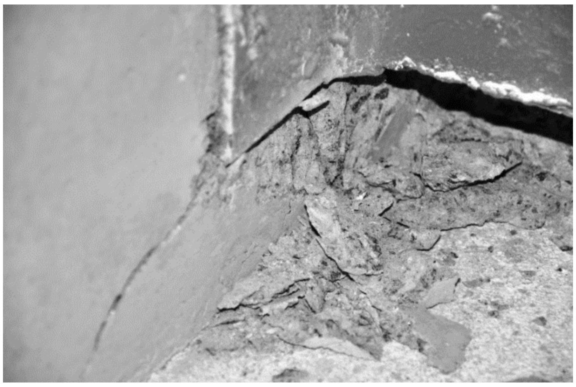


(a)



(b)

(c)



(d)

Figure 17. Failure surfaces – MAC specimens. (a) and (b) failure at the concrete block – crack orientation on the cross section; (c) longitudinal crack; (d) crushing of the concrete.

At 52 minutes of testing, registered 306,00 kN, it was possible to notice the detachment of the metal profile with the slabs in the upper region. As the test is developed, the evolution and propagation of the existing cracks in the top of the slabs in the transverse direction (Figure 17.b) as well as the still greater crushing of the concrete in the inner region of both slabs were observed. It should be noted that no new fissures appeared on any of the slabs until the end of the test, which lasted 64 minutes.

In the MAC-02 model, the first cracks appeared simultaneously in the inner region of slabs 1 and 2 in the zone below the connector, for a load of 415.60 kN. At 417,20 kN, cracks developed in the connector region, this time at the top of both slabs.

Compared with MAC-01 specimen, the first cracks occurred when the load registered corresponded to more than 90% of the maximum load that would be applied to the specimen for MAC-02, 419,80 kN noticed at the 61 minutes of test.

Before the maximum load, as the loading is increased, the development of the top cracks in the slabs is observed to propagate in the transverse direction of the slabs themselves. In addition, it was noticed the beginning of the detachment of the slabs with the steel beam in this same region

In the section corresponding to the maximum load until the end of the test, besides the evolution of the behaviors already described previously, the appearance of a longitudinal crack in the outer face of slab 1 in the direction of bottom up (Figure 17.c).

Finally, at the maximum load, the cracks present in the inner region of the slabs had already developed in a significant way, which characterizes the crushing of the concrete in that region (Figure 17.d).

The MAC-03 specimen presented an experimental behavior similar to the MAC-02 regarding the sequence of cracking. Only two facts deserve mention: a) the appearance of the first cracks occurred at a load corresponding to 82% of the maximum strength of the specimen, when it registered 335.30 kN of load; b) there was no presence of longitudinal cracks in the outer face of the slabs.

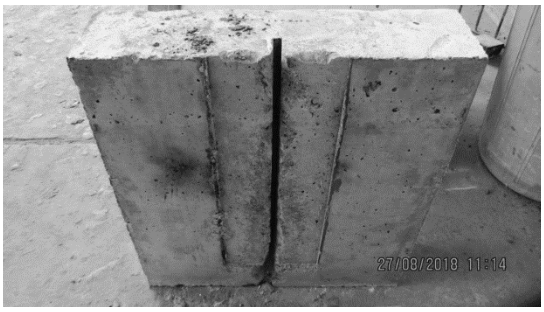
Generally, the almost absence of cracking on the external faces of the MAC specimens, as well as the slight propagation of the existing cracks, should be due to the type of slab associate with a higher reinforcement ratio. In this sense, the models presented satisfactory behavior related to the crack propagation.

In addition, after the push-out tests, an autopsy was performed on the respective specimens aiming to observe the various constituent parts in order to gather more information the behavior of the Connection by Adherence along the specimen. It was then decided to separate the slabs from the metal profiles in a deliberate and careful way.

According to the autopsies, it was observed that in all specimens there was rupture of the concrete in the region immediately below the connector, as shown in Figure 18.a to Figure 18.f.

(a) Slab 1 – MAC-01

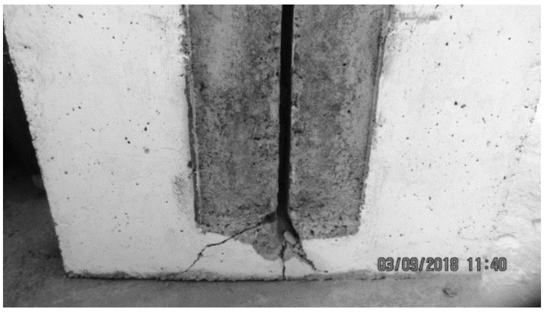
(b) Slab 2 – MAC-01



(c) Slab 1 – MAC-02

(d) Slab 2 – MAC-02

(e) Slab 1 – MAC-03



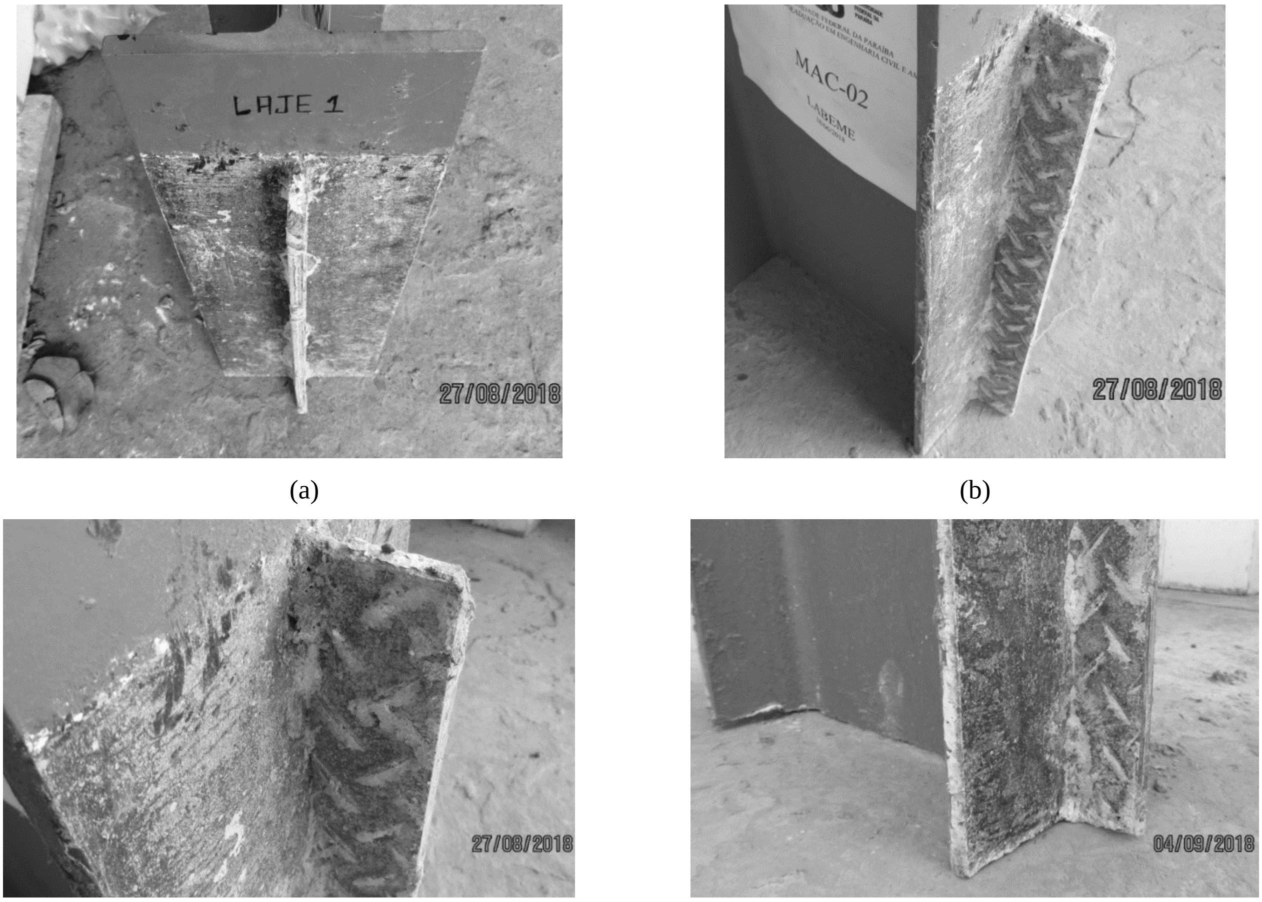
(f) Slab 2 – MAC-03

Figure 18. Autopsy of the MAC specimens.

Figure 19.a to Figure 19.d shows the final condition of the linear connectors, i.e., the post-rupture condition of the specimens. On all models, the connectors had the same characteristics.

The minor presence of concrete attached to the flange – Interface 2 – indicates that this interface had a lower contribution to the final resistance of the connection. Contrasting Interface 2, the presence of concrete attached to the linear connector's ribs (Figure 19.b, Figure 19.c and Figure 19.d) points out that Interface 1 probably contributed to a greater proportion of the final strength of connection.

Finally, Figure 19.d shows the lower region of the connector, where it was noted that in all specimens the connectors presented their physical characteristics intact. Therefore, this fact indicates that the concrete strength, as well as the presence of the concrete end-bearing zone, were preponderant factors in the connection behavior.



(a) (b)

(d) (e)

Figure 19. Final condition of the connectors (a) Flange surface; (b) Connector surface; (c) and (d) Details of the connector surface.

3.5.2.2 TREL specimens

The specimens TREL-01 and TREL-02 presented the first cracks around 61% and 76% maximum strength, being 251,00 kN and 271,60 kN respectively. In TREL-1, cracks initially appeared simultaneously on the outer face of both slabs (Figure 20.a and Figure 20.b), while in TREL-2 they appeared on slab 2 in the region near the connector at the top of the slab as well as on the interior region in the zone that is located immediately below the connector, represented by Figure 20.c. Possibly, the cracking occurred earlier in these specimens due to the arrangement of the concrete section, which makes the ribbed, suitable to cracking once ribbed slabs, in this study context, presented a low ratio of the reinforcement in comparison to the plane concrete slabs. It should be noted that, the MAC specimens are similar to those recommended by Eurocode 4 [34], while TREL specimens were made to represent commonly ribbed slabs used in the precast concrete industry.

In the TREL-01, at 290,00 kN of testing cracks appeared in the inner region of both slabs resulting from slip of the connector in that region, as well as propagation of the longitudinal crack already present on the outer face of slab 1. Before the maximum load still it was possible to observe a crack in the region near the connector at the top of the slab 1 (Figure 20.d). At this moment, when it reached 253,40 kN the TREL-01 specimen presented a certain asymmetry once slab 1 recorded about 10 times the slip recorded by slab 2, 0,88 and 0,08 mm respectively.

The maximum load of 409.20 kN for this specimen was registered after 50 minutes, associated to the sudden rupture of slab 1, characterizing an asymmetry in the behavior of the model.

Figure 20.f represents the behavior reported, i.e. one side of the specimen presented slip while other remained almost none at the end of the TREL-3 specimen test. Because of that, there was a sudden failure in the load system, which made the test continuity inviable. It should be noted that, the presented data referring to the model TREL-3 (Table 12) relates the behavior on slab 1. Similar behavior was also recorded in the TREL-2 specimen, however, there was no major problem to the test continuity.

As the load was increased, it was possible to observe the beginning of the Interface 2 failure, before to reach the load peak. Also, a higher propagation of existing cracks in the top of the slabs – in the transverse direction – as well as a greater crushing of the inner bottom region, in TREL specimens observed (Figure 20.d and Figure 20.e).

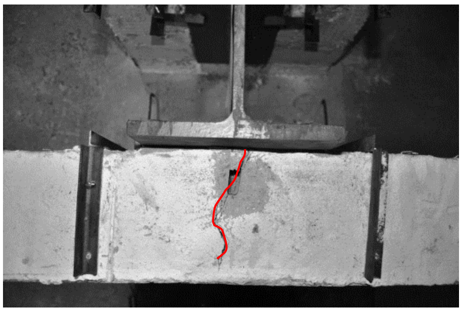
In addition, all TREL specimens presented a propagation of longitudinal cracks, from the bottom to the top, on the outer face of the two slabs that composed them (see Figure 20.a and Figure 20.b). For comparison, this observation occurred only for the specimen MAC-02.

In general, the TREL specimens presented experimental behavior slightly different than that was observed in MAC specimens. This assertion concerns both the more frequent cracks propagation on the outer face of the slabs and the asymmetry behavior of the slip, which certainly compromised the resistance of the models.

(a)

(b)

(c)



(d)

(e)

(f)

Figure 20. Failure surfaces – TREL specimens. (a) and (b) longitudinal cracks; (c) failure at the concrete block – crack orientation on the cross section; (d) crack at the top of slab; (e) failure at the concrete block; (f) asymmetry behavior of the specimen.

According to the autopsies performed, it was observed that in all the specimens there was the crushing of the concrete in the region immediately below the connector like happened in the MAC specimens. However, as shown in Figure 21.a to Figure 21.f, this fact occurred in only one of the slabs due to the asymmetry behavior of the specimens.

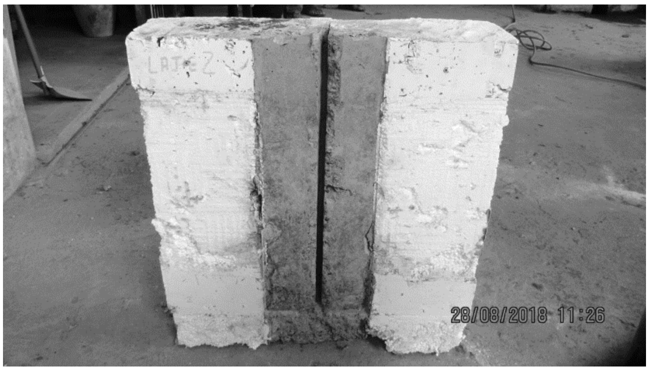
In slab 2 of the TREL-02 sample, cracks appeared in the lower rib region of the slab (see Figure 21.d), which naturally has a higher stress concentration compared to the ribs arranged at the top of the slab in these specimens. It is also a region with a higher concentration of forces, due to the arrangement of the elements that constitute the ribbed slab. Naturally, the

TREL specimens presents regions with a lower effective flange width (b_f) in comparison to MAC specimens, which are constant.

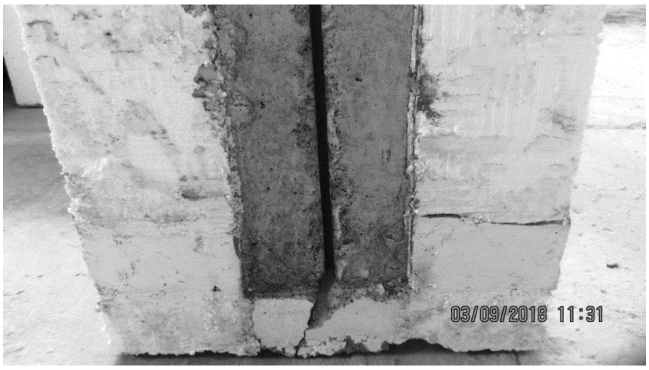
In general, the conditions presented by the connectors in the TREL specimens were similar to those observed in the MAC specimens (Figure 19), where Interface 1 certainly contributed most to the final resistance of the connection.

However, in the TREL-01 and TREL-02 specimens, a portion of concrete adhered to the junction of the connector with the flange was observed, as shown in Figure 22.a and Figure 22.b. This is believed to have occurred due to a deviation from the linearity present in the upper region of the connector due to welding failures (see Figure 22.c). This fact, however, did not delay the onset of specimen slipping, when compared to the MAC specimens, which did not present this linearity failure. It is then assumed that this portion of concrete aggregated to the connector was an eventual case.

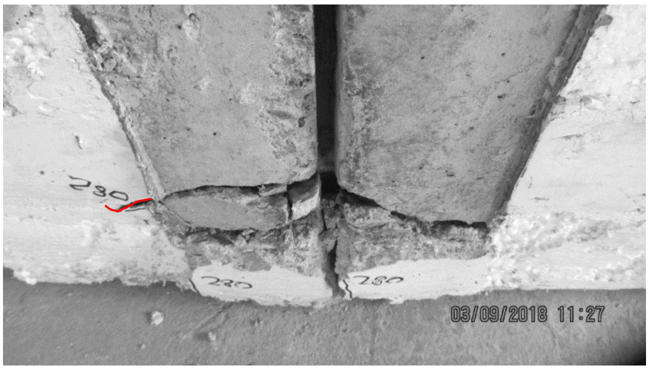
(a) Slab 1 – TREL-1



(b) Slab 2 – TREL-1



(c) Slab 1 – TREL-2



(d) Slab 2 – TREL-2

(e) Slab 1 – TREL-3

(f) Slab 2 – TREL-3

Figure 21. Autopsy of the TREL specimens.

As observed in the MAC specimens, the connectors maintained their physical characteristics intact. This indicates that the concrete resistance and the presence of concrete bearing in front of the connector edge (the concrete zone localized under the connector), end-bearing resistance, were preponderant factors to the rupture of the specimens, considering that a crack pattern was observed in this region below the connector due to a high concentration of stress. Thus, shows that of the concrete slab below the connector certainly contributes to the load capacity of the connection.

(a) (b) (c)

Figure 22. Final condition of the connectors – TREL specimens.

3.5.3 Ductility

The value of the characteristic slip (δ_{uk}) recommended by [34] to characterize a connector as ductile is at least 6 mm. That is, the connector can develop high slip values for a high load level corresponding to 90% of the maximum load. About this, in general, the Connection by Adherence for the MAC specimens demonstrated a ductile behavior, once two models presented δ_{uk} of the order of 8 mm. However, one of the connections showed no ductile behavior, in which δ_{uk} of 5.74 mm was recorded. On the opposite side, the connections referring to the TREL specimens did not present ductile behavior in general, once two specimens presented δ_{uk} of the order of 4 mm. Nevertheless, one of the specimens, TREL 01 was characterized as ductile, in which δ_{uk} of 7.00 mm was recorded.

3.5.4 Behavior uplift x slip

The uplift *x* slip behavior is important for a future analytical study because in addition to promoting the description of the deformed prototype the uplift *x* slip curve is a measure of the connection dilatancy. The uplift refers to transverse separation at the top of the specimen between the slab and the steel beam and not just a specific interface.

Once exposed, the average curves corresponding to the uplift *x* slip behavior for the performed specimens are presented (MAC and TREL specimens). They describe the kinematic law in a simplified way, as well as measure the dilatancy of the specimen.

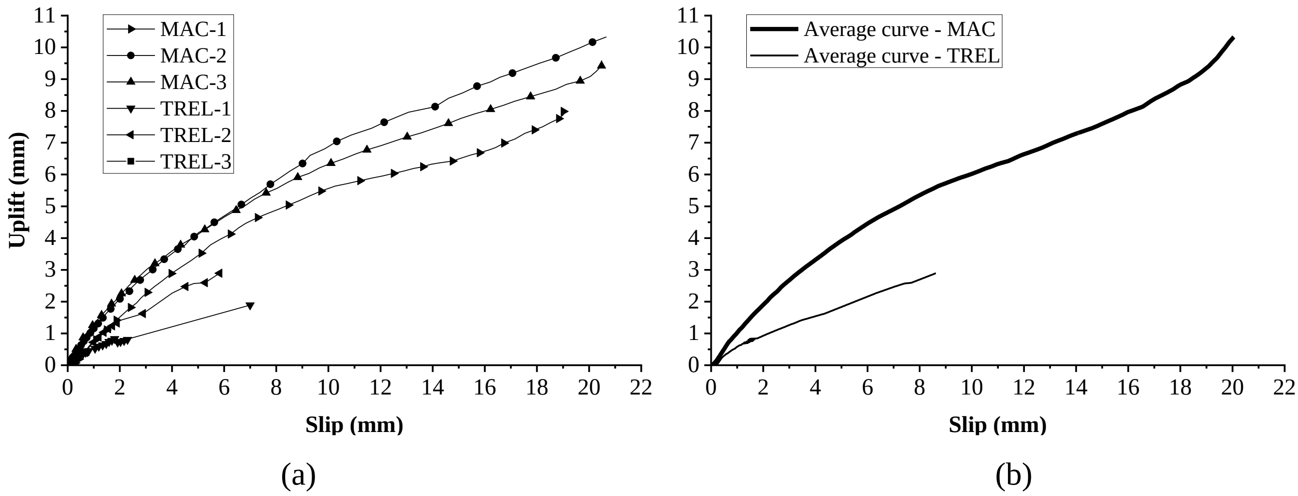


Figure 23. Results – Uplift × Slip. (a) Experimental curves (b) Average curves – MAC and TREL specimens

From the polynomial fit of the curves shown in Figure 23, we obtain equations ((1) and ((2) equations ((1) and ((2), which describe the uplift *x* slip behavior for the connectors associated with the MAC and TREL specimens, respectively.

$$Uplift = -0{,}02371.slip^3 + 0{,}46712.slip^2 - 0{,}35569.slip - 0{,}74660 \quad (1)$$

$$Uplift = -0{,}20000.slip^3 + 1{,}21399.slip^2 + 1{,}08369.slip - 0{,}09262 \quad (2)$$

As can be seen, both by the analysis of Figure 23, and by equations ((1) and ((2), there is an approximately linear trend of detachment as the slip increases, and the TREL specimens show a greater tendency to uplift in similar values of slip.

It is important to note that the above equations describe the behavior of a specific geometry of the connections by adherence, and therefore their application to other geometries and materials, although similar, should be limited to a qualitative analysis.

3.5.5 Comparison with other authors' results

In order to contextualize the proposed connector with current design practices, a comparison of the load capacity of the tested connectors with usual connectors is presented. Table 13 presents the resistance per linear meter of interface for the connector performed in this research and compares with the resistances obtained analytically for headed stud type and U-laminated connectors.

In order to determine the ultimate strength of the connectors, it was used the requirements of [41], the most common concrete classes in small and medium sized constructions – C25 and C30 – with compressive strength values of 25 and 30 MPa respectively, and 415 MPa for the tensile strength of the steel.

The comparison is performed in terms of the mean value of the ultimate strength of each connector per linear meter of interface, which can be obtained by dividing the mean ultimate resistance by twice the length of the interface evaluated (2 x 0.55 m), which resulted in 336.57 kN/m.

Table 13. Load capacity of headed studs and U-laminated connectors.

Type	**Diameter (mm)**	**Thickness (mm)**	**Load capacity/connector C25 (NBR 8800) (kN)**	**Load capacity/connector C30 (NBR 8800) (kN)**	**Connectors/length**	
					C25	**C30**
Stud	16	-	37,69	50,89	9	6
Stud	19	-	53,16	71,76	7	5
Stud	22	-	71,27	96,22	5	4
U-laminated	-	2,66	69,76	94,18	5	4
U-laminated	-	4,76	124,86	168,56	3	2

As can be seen from Table 13, in order to obtain the resistance equivalent to those presented by the proposed connectors, a large number of usual connectors are usually necessary.

A comparative analysis was developed with the results obtained by Diógenes [3] and Fernandes [10] in which connectors similar to the one proposed in this research, called Type R and PO_NERV respectively, were analyzed. This similarity is due to the linearity and dimensions of the connector, the presence of roughness and the absence of holes in the connector.

Table 14. Results obtained with linear connectors.

Type	Connector L (mm)	Connector H (mm)	Connector t (mm)	Connector Area (mm²)	f_c (MPa)	$P_{máx}$ (kN)	$\delta,P_{máx}$ (mm)	δ_{uk} (mm)
R_03	570	65	19	74100	76,37[a] 38,76[b]	395,16	0,33	0,51
R_04						283,48	0,07	0,14
R_09						310,17	0,26	0,45
R_10						346,60	0,34	
PO_NERV_1	460	80	12	73600	43,30	300,10	5,39	10,37
PO_NERV_2					43,50	279,70	5,47	9,91
MAC-1	550	50	9,5	55000	27,89	179,55	2,02	5,47
MAC-2					29,78	209,90	4,05	8,12
MAC-3					33,85	202,15	2,57	8,41
TREL-1					33,84	204,60	2,40	7,00
TREL-2					32,34	178,60	2,89	4,01
TREL-3					24,71	135,90	1,86	3,94

[a] Compressive strength of the high strength mortar (HPM) present at the interface with the connector.

[b] Compressive strength of the concrete of the specimens.

Table 14 shows data regarding the contact area of the connector in the interface under study, values of the resistance of the concrete used in the respective push-out specimens, as well as maximum load values per connector of these models together with the ductility parameters.

It is worth noting that in the research of Diógenes [3], the interface that provide the most resistance to connection by adherence was developed with high strength mortar (HPM), which certainly increased the maximum load values of the specimens. In contrast, the specimens used by this author were similar to those presented by Thomann [7], where there was no concrete immediately below the connector, thus not creating a "chock". However, the values presented by Diógenes [3] and Fernandes [10] are relatively close.

In this context, it is important to emphasize that the push-out specimens used by Fernandes [10] are similar to the models present in this research, so that the interface under study was developed between the concrete and the roughness connector.

In terms of maximum resistance per connector, on average, the values obtained by Fernandes [10] were about 40% higher than those presented in this work. However, it is worth noting that both the resistance band of the concrete used by this author was higher about 30%

as the contact area of the connector at the interface was higher 25% than the values presented in this research. Therefore, it is believed that the proposed connector made by checkered steel plate presented satisfactory result in terms of maximum resistance.

Another analysis was developed from the perspective of comparing connectors with the presence or not of ribs on their surface. Fernandes [10] compared and discussed his push-out results with results obtained by Veríssimo [42], who performed connectors with similar geometric characteristics, but without the presence of ribs. According to Fernandes [10], it was possible to estimate a gain of about 40% in the resistance due to the presence of the ribs on the surface of the connector.

In this way, it is inferred that the ribs of the connector proposed in this research show a resistance increase. However, it is necessary to carry out a new series of push-out tests under conditions favorable to direct comparison, as well as to perform complementary tests to the study.

On average the connection by adherence proposed presented a ductile behavior, as in Fernandes [10], which shows a greater capacity of transmission of forces from the steel beam to the concrete slab, when compared to the connection proposed by [3].

3.6 Conclusions

In this study, push-out tests were performed in order to propose a new shear connector by adherence with better workability, greater shear resistance and ductility so that it can be applied to several types of composite structures, mainly in buildings. The push-out specimens were fabricated and performed in accordance with Eurocode-4 requirements. Characteristics of the concrete slab were considered as variables to evaluate the effect of several design variables on the shear connector of rib from the checkered steel plate commercially used in Brazil. In addition, to validate the results obtained in this research were performed comparative analyzes with connectors proposed in other studies, as well as with usual headed studs and U-Laminated type. According to the methodology adopted and based on the results of the tests, the conclusions obtained in this study about the characteristics of shear resistance and ductile behavior are as follows:

- Connection failure is related to slip at the Interface-1, where crack formation and propagation increase with increasing load, followed by disintegration of the concrete in the region immediately below the connector.

- In all specimens, slabs ruptures in the region immediately below the connectors and remained intact at the end of the tests. In this way, the rupture of the models - with the use of solid reinforcement or prefabricated slabs - is associated mainly with the rupture of the concrete;
- The specimens with prefabricated slabs were more propitious to the appearance of cracks, contrasting specimens with solid slabs that presented a greater forces transmission capacity between the connector and the concrete slab;
- Specimens with prefabricated slabs showed asynchronous slip on both slab;
- The models with the use of prefabricated slabs, if better designed with regard to the improvement of the forms and the cast process, would certainly avoid the asymmetric behavior and would present, on average, resistances of the same order of magnitude obtained models with the use of solid slabs. That is, the use of lattice prefabricated slab probably was not a negative factor to the final bond strength by using linear connectors;
- Interface 1 - Connector/Concrete certainly was the most contributed to the connection resistance;
- Specimens with prefabricated slabs have higher uplift values as slip increases compared to solid reinforcement slab models;
- The Connector by Adherence made with checkered steel plate certainly exhibited satisfactory performance in terms of ultimate shear resistance and ductility. Thus, it is believed that it is appropriate to use this type of connector in composite steel-concrete structures.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

During the development of the present investigation and in accordance with the objectives established in item 1.2, we sought to characterize the behavior and quantify the strength of a new proposal for connection by steel-concrete adherence, through an experimental approach. This composite connection consists of the application of a checkered steel plate as a shear connector in the context of ribbed slabs. Also, according to the initial proposal of the research, it was considered convenient and of high interest to conduct a systematic review about linear shear connectors in order to discuss their use in residential and commercial structures.

Regarding the systematic review, it was found that linear connectors offer sufficient shear strength and ductility characteristics by comparison to usual shear connectors such as headed studs. It should be noted that the review included studies with different methodological variables regarding the Push-out test, which allowed us to propose further discussions on linear shear connectors. In this context, it is understood that it would be technically feasible to use these connectors in composite structures of residential and commercial buildings.

From the systematic review it was possible to perform a quantitative analysis of the results presented in the studies included in the review, considering shear strength aspects of the proposed connections. In this context, it was observed that the ultimate shear bond strength is strongly associated with the compressive strength of the material present at the interface with the connector.

Regarding the experimental approach, it is understood that connection by adherence presented high ultimate shear resistance when compared to the connections from usual connectors, such as Studs, this being proven by push-out tests. In addition, the connection by adherence formed by checkered steel plate had satisfactory ultimate shear resistance and ductility compared to other types of linear connector by adherence or Perfobond connectors.

In the context of Push-out tests, it is important to highlight that, in general, the strength of concrete slabs was a limiting factor for the rupture of the specimen. Most of the connectors were classified according to Eurocode 4 [34] as ductile, to be used in solid or ribbed slabs.

Also, it is imperative that further tests be performed in order to identify the shear resistance portion associated with the checkered steel plate connector ribs, as well as the shear resistance portion referring to the transverse reinforcement when used. This would make it possible to give better characterization to this connector.

Thus, from the experimental program, which evaluated and discussed aspects of the structural behavior of the proposed connection from linear connectors formed by ASTM - A36 chess type plate, evidence was extracted in order to present a perspective on its applicability in residential construction in the context of ribbed slabs.

Finally, it was believed that in a short time the connection by adherence could become a viable option in the construction of residential buildings, provided that new research is carried out. In this sense, it is recommended:

- ✓ Push-out tests

It is believed that as a natural consequence, after deepening the knowledge about the connection proposed in this research, changes in geometry and materials would provide new perspectives for the connection by adherence.

Thus, to evaluate the ultimate shear capacity of the performed connector considering the variation of the compressive strength of the concrete, as well as the thickness variation of the concrete slabs. In addition, to evaluate the structural behavior of the composite connection considering the presence of holes and transverse reinforcement.

- ✓ Direct shear and Pull-out tests

The determination of the rupture criterion for each interface, concrete-concrete, concrete-connector, was something that this study could not cover. Thus, performing direct shear tests (Figure 24.a) for confinement levels ranging from 0,5 to 5 N/mm² is the way to be followed in order to determine the mentioned behaviors and thus enable a more representative numerical analysis. This test also aims to evaluate the deformation kinematics of the composite connection.

Complementing the direct shear tests, it is suggested to perform pullout tests, standardized by CEB [43] and ASTM [44] (Figure 24.b) in order to evaluate the adherence of the composite connection developed under tensile stresses, which is interesting to know due to uplift.

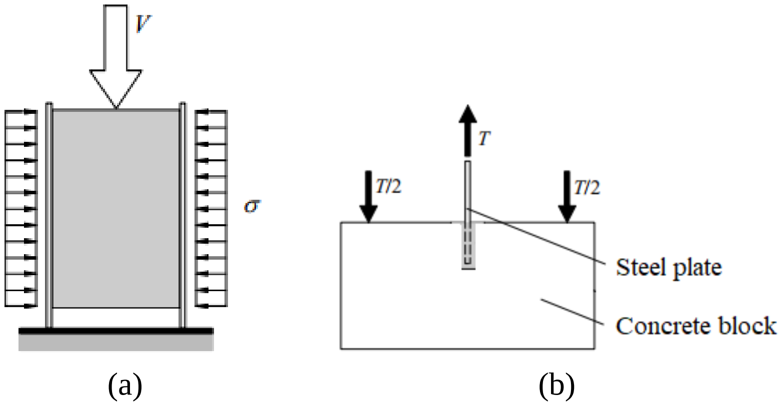


Figure 24. (a) Principle of the direct shear test principle. (b) Principle of the pullout test.

✓ Flexural test

Performing Flexural tests subjected to static and dynamic loading in order to evaluate the connection under simulated conditions of use. In addition, this test allows to evaluate:

a. The level of shear connection on the composite section, by comparison solid slabs with ribbed slabs.
b. The stiffness, strength and deformation capacity of the designed connectors when included in a composite beam.
c. The level of interaction of the composite section, by comparison solid slabs with ribbed slabs.
d. The connection behavior under load applied perpendicularly to the concrete slab. The slab self-weight, along with the loads applied perpendicularly, influence the connection strength since they create confinement in the connection region. In the push-out tests usually performed, there are no loads applied perpendicularly to the concrete slab and therefore there is less restriction to uplift displacements. According to Thomann and Lebet [8], the constitutive and kinematic laws (i.e. relationships of normal stress–maximum shear, slip–shear stress and slip–uplift) for these types of connections are strongly dependent on the normal stress; the normal stress acting on the interfaces in a connection by adherence is not constant but increases with increasing slip.

- ✓ Finite element analysis

Validate a finite element numerical model using a computational package that satisfactorily represents the results obtained with the proposed experimental tests, allowing to extrapolate the results according to proposed methodological variations, and allow parametric studies to be performed.

- ✓ Economic analysis

Economic and commercial feasibility study on the use of linear connectors formed by ASTM - A36 chess type plate in building construction.

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