Federal University of Paraiba
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– MASTER'S DEGREE –

NEW ALTERNATIVE FOR CONNECTIONS BY ADHERENCE: COMPOSITE BEAM TESTS

By

Kildenberg Kaynan Felix Nunes

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

João Pessoa – Paraiba **October, 2019**

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

Candidate: Kildenberg Kaynan Felix Nunes

Advisor: PhD. Hidelbrando José Farkat Diógenes

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APPRAISAL BOARD:

Prof. Dr. Hidelbrando José Farkat Diógenes – UFPB
(Advisor)

Prof. Dr. Normando Perazzo Barbosa – UFPB
(Internal evaluator)

Prof. Dr. Rodrigo Barros – UFRN
(External evaluator)

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I dedicate to my parents

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À Deus!!!

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ABSTRACT

In the last years, it was observed a great process of industrialization of construction and the in countries with emerging markets that triggered the search for building systems that could be more efficient. In this context, steel-concrete composite structures seem to be a formidable candidate to attend this demand. Another relevant question is the types of concrete slabs, one that is usually used in small buildings in the Brazilian market are the ribbed slabs, thus deserving also a detailed investigation on how this type of slab behaves in the context of composite structures. In the context of composite beams, Adherence connection, where the resistance is due to adhesion, friction, and interlocking between several interfaces, is a particularly promising solution. Thus the scope of this research was to evaluate the applicability of connections by adherence in the context of ribbed slabs type concerning its flexural behavior. For that, it was done a systematic literature review to understand the flexural behavior and functioning of adherence connections better. Besides, it was evaluated and discussed aspects of the structural behavior of distinct composite beams based only on the slab typology through an experimental program (Flexural and Dynamic tests), where the connection by Adherence was obtained by a checkered steel plate welded on top flange of the beams. From the systematic review, it was possible to do a qualitative analysis of principal aspects of these composite structures with linear steel connectors. From the experimental program, it was possible to evaluate the behavior of a new alternative for connection by adherence, with different types of slabs, ribbed and solid, composite beams with ribbed slabs showed better results, achieving until 83.32 % of level of interaction, while the beams with solid slabs obtained the maximum degree of interaction of 75.29 %. Regarding the dynamic tests, it was possible to measure the reduction in the bending rigidity of the composite beam after the static tests indirectly. Thus, from the experimental program and the systematic review, At last, it can be said that linear connectors formed by a checkered steel plate can be used in composite beams built with solid or ribbed slabs, being a viable option for structural engineering.

KEYWORDS: Shear connector; Flexural Behavior; Ribbed slabs; Connections by Adherence.

RESUMO

Nos últimos anos, observou-se um grande processo de industrialização da construção e nos países com mercados emergentes que desencadeou uma busca por sistemas construtivos mais eficientes. Nesse contexto, estruturas mistas de aço e concreto parecem ser uma opção formidável para atender a essa demanda. Outra questão relevante são os tipos de lajes de concreto. Um tipo de laje que normalmente e utilizada em pequenos edifícios no mercado brasileiro, são as lajes nervuradas, merecendo, assim, uma investigação detalhada sobre como esse tipo de laje se comporta no contexto de estruturas mistas. No contexto de vigas compostas, a conexão de aderência, onde a resistência é devida à adesão, atrito e intertravamento entre várias interfaces, é uma solução particularmente promissora. Assim, o objetivo desta pesquisa foi avaliar a aplicabilidade das conexões por aderência no contexto do de lajes do tipo nervurada em relação ao seu comportamento à flexão. Para isso, foi realizada uma revisão sistemática da literatura para entender melhor o comportamento à flexão e o funcionamento das conexões por aderência. Além disso, foram avaliados e discutidos aspectos do comportamento estrutural de vigas mistas distintas, baseado na tipologia da laje, através de um programa experimental (ensaios de flexão e dinâmicos), onde a conexão por aderência foi obtida por meio de uma placa de aço xadrez soldada na mesa superior do perfil metálico. A partir da revisão sistemática, foi possível fazer uma análise qualitativa dos principais aspectos dessas estruturas mistas com conectores de aço lineares. A partir do programa experimental, foi possível avaliar o comportamento de uma nova alternativa de conexão por aderência, com diferentes tipos de lajes, nervuradas e maciças, as vigas mistas nervuradas apresentaram melhores resultados, atingindo até 83,32% do nível de interação, enquanto as vigas com lajes sólidas obtiveram o grau máximo de interação de 75,29%. Em relação aos ensaios dinâmicos, foi possível medir, indiretamente, a redução da rigidez à flexão da viga composta após os ensaios estáticos. Assim, a partir do programa experimental e da revisão sistemática, finalmente, pode-se dizer que conectores lineares formados por uma placa de aço xadrez podem ser utilizados em vigas compostas construídas com lajes sólidas ou nervuradas, sendo uma opção viável para a engenheiros estruturais.

PALAVRAS-CHAVE: Estruturas mistas; Conector de cisalhamento; Lajes nervuradas; Aderência.

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CHAPTER 1

INTRODUCTION

1.1 CONTEXT AND MOTIVATION

In the last years, it was observed a great process of industrialization of construction and in countries with emerging markets that triggered the search for building systems that could be more efficient. In this context, steel-concrete composite structures seem to be a formidable candidate to attend this demand once they can provide very competitive solutions when it comes to simple, fast, and economical construction that can accompany the requirements for quality, aesthetics, and cost.

The Brazilian Association of Technical Standards (ABNT) NBR 8800:2008, Design of steel structures and composite steel and concrete structures of buildings, deals with composite steel and concrete structures consisting of steel and concrete components, whether or not reinforced, with a mechanical connection provided by shear connectors between the steel component and the slab in such a way that both function as a set to resist bending.

According to Valente and Cruz (2006), a composite action can be obtained by reducing the relative displacement at the interface between steel and concrete by the use of shear connectors, so the two materials deform as a single element. For example, the system of Figure 1 formed by simply supported steel beam supporting a concrete slab in its upper face, with and without composite action. When the beam is simply supported, it contributes to the efficiency of the composite system, since the steel beam works predominantly to the tension and the concrete slab to the compression, although it is not often the most economical solution.

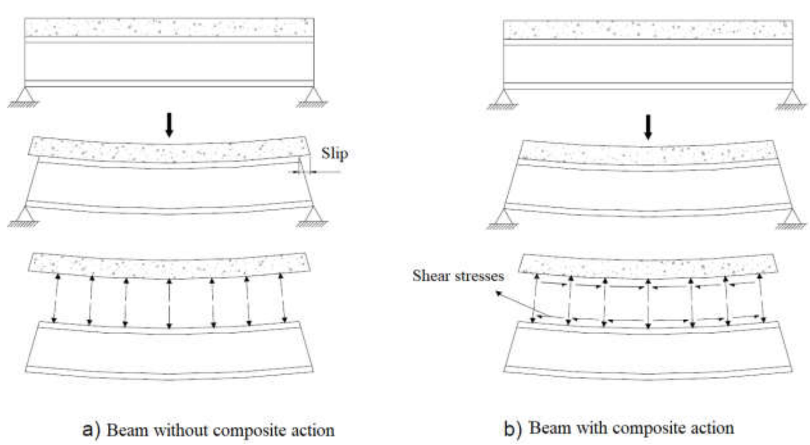


Figure 1 - Composite beams (David, 2007)

Thus, the objective of this assembly is to combine high tensile strength of the steel and high compressive strength of the concrete. In this way, the resultant composite beam section is stiffer and resistant than a steel girder or the concrete slab alone.

Nevertheless, the connection method between the concrete slab and the steel girder is vital for the durability and mechanical behavior of the steel-concrete composite structures, so it is evident, the need for the presence of connectors that can guarantee the most efficient connection between them.

Another relevant question is the types of concrete slabs that will be used, one that is usually used in small buildings in the Brazilian market are the ribbed slabs (Figure 2), thus deserving also detailed investigation on how this type of slab behaves in the context of composite structures.

In the assembly or execution of the ribbed slabs, the ribs are placed spaced, and the filling of these spaces is made by light elements, usually EPS blocks (expanded polystyrene) or ceramic tiles. Those inert materials have the function of replacing part of the concrete in the tensioned region of the slabs, as well as serving as a form for on-site cast concrete. In this type of element, the concrete below the neutral line – from de top to the bottom of the slab – is concentrated in the ribs, which provides savings in terms of materials, labor, and shape. The reinforcement of ribs is formed by the presence of a lattice joist, which is a structure formed by an 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.

(a) (b)

Figure 2 - Execution of a precast ribbed slab in a steel structure building. (David, 2007)

It is essential to understand how the connection between two different materials behave and how the stresses in those interfaced are transferred. For the steel-concrete interface, much research has been carried out in the field of shear behavior, these being more directed to steel bars. However, these researches are still very limited regarding the geometry under study (steel bars connected to concrete).

Steel-plate studies have been carried out, including Beck and Heunisch (1972), who studied the friction between flat steel plates and precast concrete blocks and, more recently, Mangerig and Zapfe (2002), a series of tests between in-situ molded concrete blocks and smooth steel plates.

Kitoh and Sonoda (1996) studied the shear strength of the interface between a steel plate with grooves perpendicular to the shear direction, called ribbed plates. Sonoda et al. (2000) performed the same study, but now for oblique and discontinuous grooves the shear direction, this type of surface called checkered plates.

Finally, Sonoda et al. (2000) concluded that the use of grooves is effective in improving steel-concrete adherence. The authors do not indicate the best typology for grooves, but from the evaluation of their results, it can be inferred that the use of checkered plate grooves implies a higher ultimate strength.

It should also be noted that the studies carried out by Kitoh and Sonoda (1996) and Sonoda et al. (2000) were experimental. Currently, the use of calculation models that allow the determination of shear strength is limited, applying only to structures with specific geometries. Figure 3 illustrates the types of slots used by these authors.

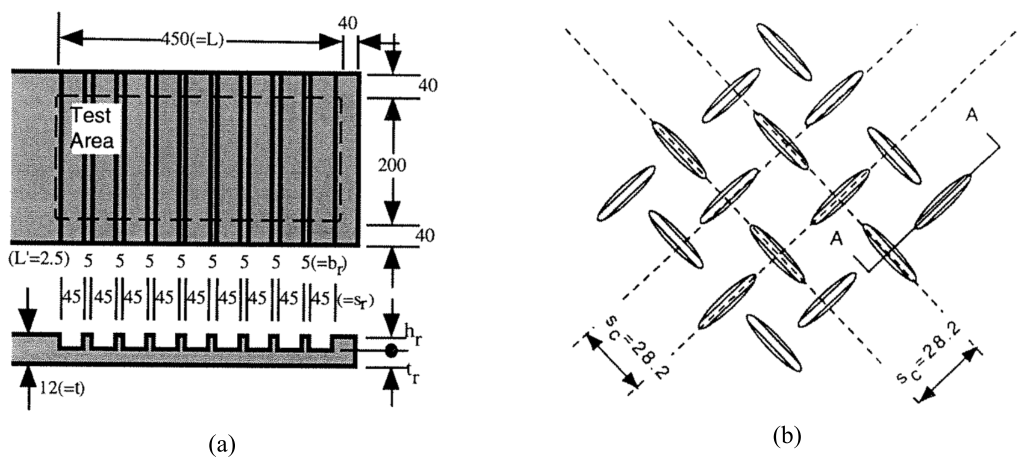


Figure 3 - Grooves: (a) ribbed plates: (b) checkered plates (Sonoda *et al.*, 2000)

Also, according to Chen *et al.* (2018), that studied beams encased by plates with a checkered pattern on the surface, this pattern can substantially improve the bonding effect between the steel and concrete.

For the connection between steel beams and concrete slabs, aiming reducing construction time and improving building durability without increasing the cost of the solution, the development of new types of connections is necessary. Connections by adhesion, interlocking, and friction (called "Connections by Adherence" by Thomann (2005)) seems to be quite promising (Diógenes *et al.*, 2015) to obtain a practical, economical and fast solutions for connections in steel-concrete composite structures.

Those connections could be obtained by a straight steel connector with grooves on its surface. Based on the premise that the field of study on the subject is still developing concerning the variability of geometries and constructive dispositions, it is indisputable the scientific and market importance in mastering knowledge regarding the use of composite structures, connected through adherence, as conventional structural elements.

Therefore, the comprehensive study of the adherence behavior in composite structures has the potential to improve the calculation models for design, as well as the establishment of experimental analysis for the evaluation of existing structures.

It is believed that a comprehensive and systematic review (SR) of the literature related to the flexural behavior of Connections by Adherence can provide a better understanding of how those connections improve the solutions for composite structures.

It should be noted that the SR's are different from the traditional literature reviews, once they seek to collate all evidence that fits pre-specified eligibility criteria to address a specific research question. (Higgins JPT, 2011). When comprehensive bibliographic research is conducted transparently, impartially, and logically, it can be considered a "Systematic Review" (Neely *et al.*, 2009).

1.2 OBJECTIVES

The general aim of this research is to evaluate through a Systematic Review and experimental program, the applicability of Connection by Adherence, obtained by a checkered plate (Figure 4), between steel and concrete in the context of ribbed slabs, in order to offer foundations to researchers and engineers of structures regarding the use of these connections in small buildings.

Figure 4. Checkered plate.

Thus, to achieve the general objective, some specific goals were established:

- Study and understand the flexural behavior and functioning of adherence connections in the face of a systematic literature review;
    - Discuss key concepts, findings, and recommendations in previous research;
    - Synthesize from the earlier studies, maximum shear strength, cracking panoramas, and connection parameters, such as load-slip (load x slip) behavior and load x vertical displacement.
- Evaluate and discuss aspects of the structural behavior of distinct composite beams based only on the slab typology through an experimental program (Flexural and Dynamic tests).
    - The undamaged and damaged level of shear connection on the composite section, by comparison with solid and ribbed slabs.
    - The stiffness, strength, and deformation capacity of the designed connectors when included in a composite beam.

1.3 BRIEF REVIEW OF COMPOSITE BEAM CONNECTION

Welded studs connectors are widely used in composite steel-concrete beams (Pathirana *et al.*, 2016). However, the stud-type connector concentrates stresses and cause intense cracking in the connection region. So, Alternatives to steel beam–concrete slab connections without the use of the usual stud-type connectors have been studied for some time.

Interesting research using these ‘alternative’ systems has been carried out by Yamane *et al.* (1998), Shim *et al.* (2001), Schmitt *et al.* (2004), Veríssimo *et al.* (2006), Thomann and Lebet (2007), Bouazaoui *et al.* (2008), Hegger *et al.* (2010), Papastergiou and Lebet (2011) and (Diógenes *et al.* , 2015). Some of these studies used cast-in-place slabs, but it is also possible to consider the use of prefabricated slabs.

Research has now advanced on linear connectors. Connections using straight connectors (Figure 5) are characterized by continuity in the distribution of stresses, thus minimizing stress concentration implications in the concrete slab, which justifies the current context.

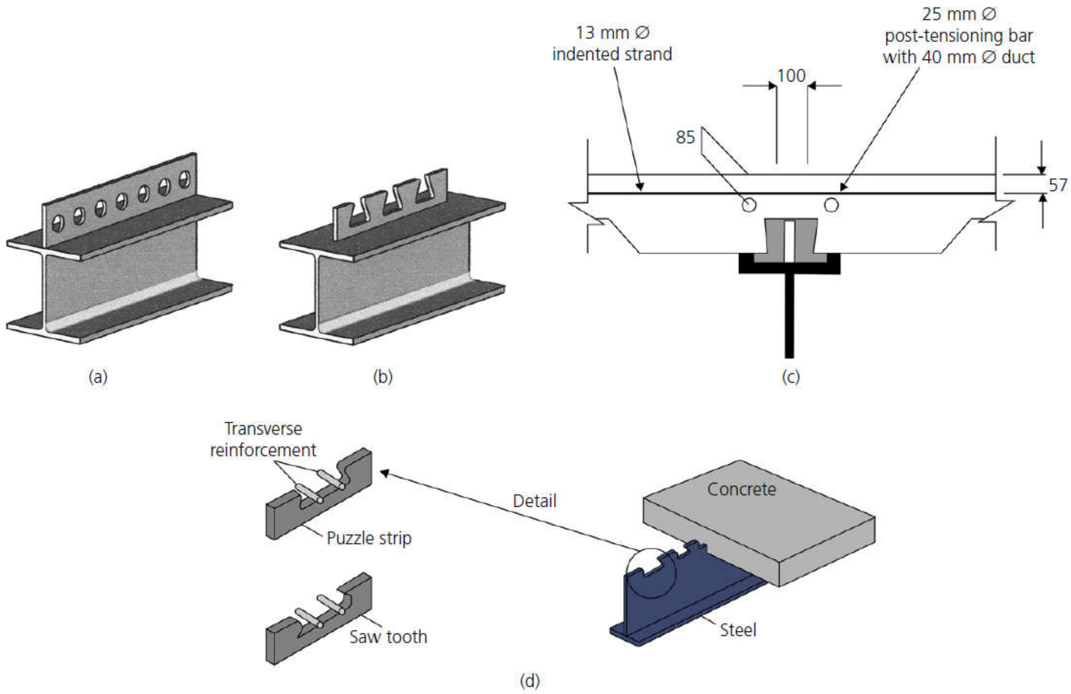


Figure 5 - Alternatives to steel beam-concrete slab connection without the use of the usual stud-type connectors: (a) linear connector Perfobond (Veríssimo *et al.*, 2006); (b) crestbond connector (Veríssimo *et al.*, 2006); (c) longitudinal rib (Yamane *et al.*, 1998) (dimensions in mm); (d) similar idea to crestbond proposed by Hegger *et al.* (2010). Adapted from (Diógenes *et al.*, 2018)

For this reason, Leonhardt *et al.* (1987) proposed the first linear connector called Perfobond. The Perfobond consists of a flat steel plate with circular holes, welded onto the top table of the steel beam, idealized from the need to have a connector that does not allow friction between the steel and the concrete, and at the same time, only elastic deformations for service loads.

Some studies can be cited, from those who studied its application in normal weight concretes, such as Oguejiofor and Hosain (1994) and Studnicka *et al.* (2002), to researches evaluating the use of Perfobond in lightweight concretes, such as that of Valente and Cruz (2004). Other investigators also examined the behavior of the Perfobond in the application of these in composite structures in order to take advantage of its higher resistance to shearing, easy manufacture, etc. (Ahn *et al.*, 2010; Mohammad *et al.*, 2011; Xue *et al.*, 2012; Shim *et al.*, 2011; Shariati *et al.*, 2011).

Considering a disadvantage of the Perfobond connector, which is the difficulty in positioning the lower reinforcement of the slab, Veríssimo *et al.* (2006) proposes the connector CR (Figure 5 b), formed by an indented plate, allowing, then, more efficiently the arrangement of the bars. According to Diógenes *et al.* (2015), this type of connector confers resistance to longitudinal shear and prevents uplift, which is the transverse separation between the metal beam and the concrete slab.

Vianna (2009) proposes the T-Perfobond connector, whose main difference for the Perfobond connector is the presence of a table that provides a more efficient anchorage to the system (Figure 6). This connector combines the high strength of the block type connector with the ductility and resistance of the holes in the Perfobond. According to the author, the advantages of using these types of connectors are high strength, easy manufacturing and installation, and good performance in fatigue behavior.

Figure 6 - T-Perfobond connector (Vianna, 2009).

Another alternative is the Connections by Adherence, initially studied by Thomann and Lebet (2007), Papastergiou and Lebet (2014), and Diógenes *et al.* (2015), by presenting a group of full-scale flexural tests of composite beams. Some of the results of push-out tests performed by Dauner (2002) and Thomann (2005) are illustrated in Figure 7. It can be seen that the Connections by Adherence exhibit very high shear resistance and stiffness compared to Headed Studs and Perfobond.

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 (Diógenes *et al.*, 2015)

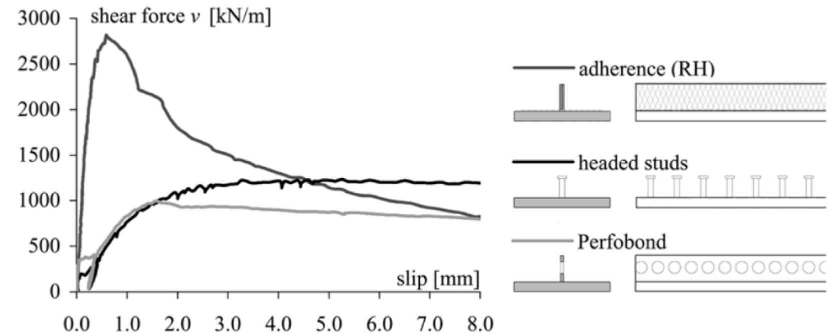


Figure 7 - Comparison between different connection types. (Thomann and Lebet, 2008).

Connections using Perfobond require transverse reinforcement and concrete aggregates through the holes to reach high resistances, according to Leonhardt *et al.* (1987). When using a full-depth precast slab and a cement-paste injection, neither transverse reinforcement nor aggregates can contribute to the shear resistance. A Perfobond connection is consequently not an efficient connection between a steel beam and a full-depth precast slab, but Connections by Adherence do not need any transverse mechanical anchor to resist shear forces, thus making it possible to use them with full-depth precast slabs and an injection of cement paste (Thomann and Lebet, 2008).

Diógenes *et al.* (2015) in his research proposed a new type of connector in front of variations imposed on the model of Thomann and Lebet, (2007) in terms of geometry, altering characteristics in steel surface as well as introducing holes, as shown in Figure 8. In the study of Diógenes *et al.* (2015), it was observed that no significant differences in resistance and slip were found to justify the use of the hole in the straight connector. However, the author emphasizes that the presence of holes allows the passage of reinforcement when it is necessary to increase both the resistance and the ductility of the connection, although in that work was used reinforcement through the holes.

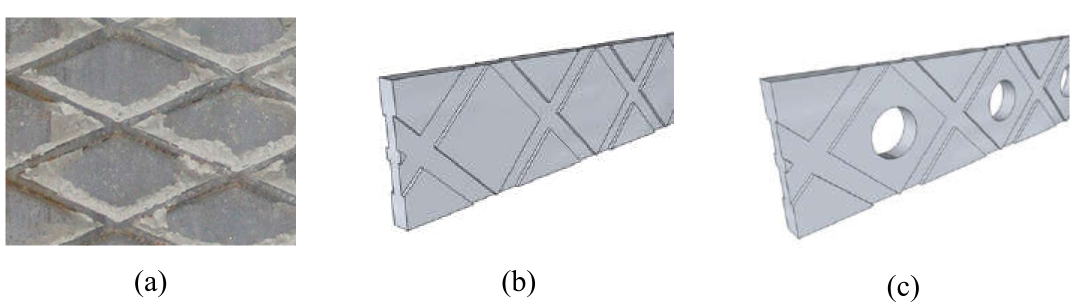


Figure 8 - Examples of grooves used in steel plates: (a) plate used by Thomann & Lebet (2007), (b) Connector R e (c) Connector RP by Diógenes *et al.* (2015).

An adherence connection has been developed to simplify both the choice of materials and construction methods. Rather than what is proposed by this research, a very suitable example is illustrated in Figure 9, present in the study by Thomann and Lebet, (2007). It corresponds to a prefabricated concrete slab, with a longitudinal groove, supported by a steel beam. This beam, on the other hand, has a straight connector with a rough surface on the upper flange. Still on the top flange, one applies a roughness (adhesive layer), increasing the coefficient of friction and, consequently, the resistance of the bond.

At the surface of the groove of the slab in contact with the cement mortar, a certain roughness is applied by chemical or mechanical means, and after the pre-fabrication of the precast slabs, the cement mortar is injected between the precast slab and the steel beam.

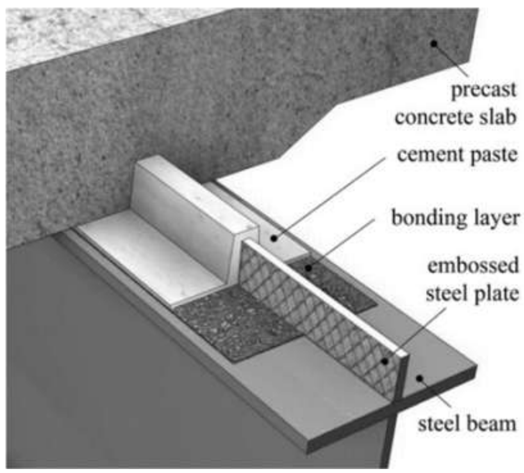
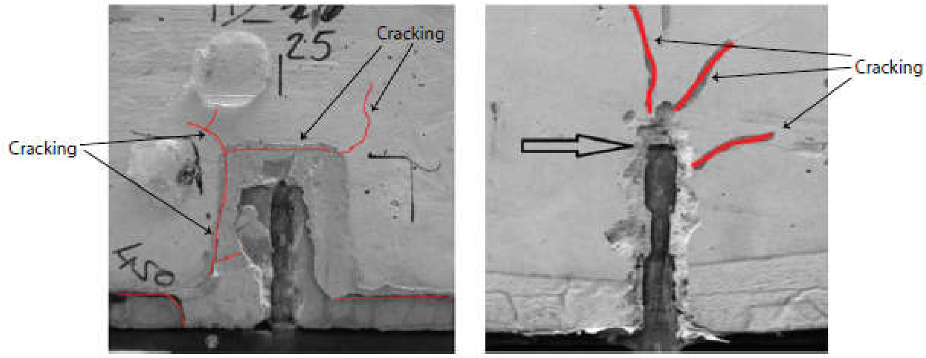


Figure 9 - Example of adherence connection (Thomann and Lebet, 2007).

Based on the study performed by Thomann and Lebet (2007), Diógenes *et al.* (2015) presented the objective of evaluating the connection by adherence under conditions similar to those of use, in which an experimental program consisting of tests of the types push-out and flexural tests of composite beams, being subjected to non-destructive static and dynamic loads. Therefore, Diógenes *et al.* (2018) analyzed prototype composite beam prototypes with different connector types and constructive arrangements, which were produced, for example, with cast-in-place and prefabricated slab, as shown in Figure 10.



(a) (b)

Figure 10 - (a) Precast slab connection; (b) Cast-in-place slab connection (Diógenes *et al.*, 2018).

According to the author, the prototypes presented a high degree of interaction in the composite section, where the prototypes made with prefabricated slab showed a degree of interaction of the order of 80% of those made with solid slab cast-in-place showed full shear connection. Nevertheless, complementary studies need to be performed.

1.4 METHODOLOGY

After the brief review of the composite action in structures and how this could be achieved for beams, one must see that there is already useful information about connection by adherence, but that information can be synthesized to get new evidence about the use of this connection. However, even with some works already published about the subjected, there is still a lack of information on how changes in the geometry of properties of the material of the structural elements can influence the composite behavior.

Given this, 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 the flexural behavior of connections by adherence, but present independent discussions, which allows the analysis in question from two different perspectives.

In the systematic review of the 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 straight connectors in steel-concrete composite structures. This review made it possible to judge the flexural behavior of this type of connection 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 doing material characterization tests together with flexural tests of full-scale composite beams to analyze the flexural behavior and compare distinct composite beams based only on the slab typology (solid and ribbed). Also, dynamic tests were performed to verify the level of shear connection of the undamaged and damaged specimens (before and after the flexural tests, respectively).

1.5 DISSERTATION STRUCTURE

The present study was subdivided into four chapters described in the following topics:

- Chapter 1: A brief introduction and review of literature, as well as an explanation of the general and specific objectives with the methodology to achieve those goals.
- Chapter 2: The description of a Systematic Review performed to get evidence on how connection by adherence behaves in flexural action.
- Chapter 3: Presentation of an experimental program of a new alternative for connections by adherence and discussions.
- Chapter 4: The final considerations of this work based on the proposed objectives by summarizing the analysis of the results from the Systematic review and the experimental program.
- Appendix A: Presentation of the analytical calculation of the composite beams bending strength according to NBR 8800:2008.
- Appendix B: Presentation of the analytical calculation of the natural frequency of the composite beams.

CHAPTER 2

SYSTEMATIC REVIEW

It is challenging to know all the knowledge already published in a topic area with the constant growth of research and a large number of articles published all over the world. For that, a Systematic Review (SR) comes with a different approach from traditional literature review. A well-executed SR is a rigorous and replicable approach to identifying, evaluating, and summarizing scientific evidence relevant to a specific clinical or policy question (EFSA, 2010).

Further, summarize the existing evidence in a topic, identify gaps in state of the art to propose areas for further investigation and to provide a framework to appropriately position new research activities are three main reasons for performing a literature review (Muller *et al.*, 2019). Zumsteg *et al.* (2012) recommend that, at a minimum, a SR's protocol include five key components:

I. a general description of how studies or data will number 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 or meta-analysis;
IV. a clear plan for recording and summarizing data from the different studies, including what parameters or data points are of interest;
V. if any, meta-analyses are planned.

In a simplified way, a SR can be described as a structured literature review associated with a synthesis of the evidence from this set of works, aiming to answer a specific question or application. It is generally published to share these results with a broad audience for consideration and implementation.

2.1 METHODS

For the SR, the primary source of information was Scopus, officially named SciVerse Scopus, introduced by Elsevier Science in 2004. Web of Science and Scopus are the most comprehensive databases which are frequently used for searching the literature. However, Scopus covers a superior number of journals (Chadegani *et al.*, 2013).

2.1.1 Planning the review

Previously, a group of four researchers was invited to contribute to the research protocol, being two Experts – which are professors – on the topic of this work. 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 was defined, the search strategy, and criteria of exclusion beyond the method of synthesis. According to the main objective and scope of this SR, the proposed research question was: *How is the flexural behavior of connections by adherence?*

2.1.2 Study identification

This process was initiated by building a comprehensive set of search terms that relate to the level of interaction on composite structures. These were concatenated into a search string using a series of Boolean 'AND' and 'OR' operators. It was applied a limit to the subject area, and none for language or year of publication. All other search refinement options have not been changed. The Scopus® database was adopted using the strategy presented in Table 1.

Table 1 - Parameters used in the researches

	Research 1	**Research 2**	**Research 3**	**Research 4**
First field	*Connection by adherence* OR *shear connect**	*Perfobond connector* OR *Perfobond rib connector* OR *Perfobond shear connector*	*Y-shaped* OR *T-shaped* OR *I-shaped* OR *Y-type* OR *T-type* OR *I-type* OR *"CR connector"* OR *Crestbond*	*Interlocking* AND *Friction* AND *Adhesion*
Operator	*AND*			
Second field	*Steel-concrete* OR *interaction* OR *composite beam*			

Thus, the researches were carried out in June of 2019. These citations were downloaded and exported to the reference manager Mendeley® for the selection of studies.

2.1.3 Study selection and quality assessment

The selection process began by selecting potential relevant articles through a title and abstract scan of citations. After that, the duplicated citations and citations that explicitly match the exclusion criteria were excluded 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 an in-depth review. The exclusion criteria are listed in Table 2.

Regarding the exclusion criteria No. 5, it was also accepted works with composite slabs that were stressed in just one direction, i. e., the same behavior of composite beam but with a smaller height. And for the exclusion criteria No. 6, the focus of this work is how the connections by adherence behave in flexural action, but since the study about this type of connection is relatively new, it was studied all continuous linear connectors since they have all similar characteristics and to get more evidence about the differences in the behavior of the connections by adherence.

Table 2 - Exclusion criteria

No.	Criteria	Reason for exclusion
1	Just article and review as document types	Another type may not be relevant
2	*Qualis* - CAPES higher than or equal to B2 /or have JCR	a. Quality and Validity of research b. To reduce biased data synthesis
3	Full-text articles unavailable electronically	Resources and time isn’t available to gather them
4	Non-English language	May not be relevant and widely disseminated academically
5	Do not address experimental flexural behavior from composite beams.	Composite flexural behavior is the focus of the work
6	Do not address continuous linear connectors	The interaction provided by the connectors are the focus of the work

The researches screened the articles according to pre-specified inclusion and exclusion criteria and independently extracted the data. Any disagreements were 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 a methodological procedure, compliance, and data reliability. For this, criteria were selected to evaluate the quality of the study to ensure that sufficient rigor has been applied to the conduct of each research project. 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*. Besides, it was used 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 or equal to B2 or have a JCR.

2.1.4 Data extraction and synthesis

The data extraction must be directly linked to the review question and the criteria to assess the eligibility of the studies. Within the SR, the removal of duplicate data is a common feature designed to improve reliability, increase accuracy, and validate data interpretation. Thus, the reviewers independently assessed each research presented in Table 1. Each person extracted the data in a table of predefined evidence. Subsequently, the two tables were compared, and any disagreements were resolved through discussion with the expert.

Qualitative data collected from each article include:

- The main idea of the object of study application;
- Methodological procedures adopted in the experimental program;
- A complete description of the connectors and the composite connection;
- Values of the maximum load capacity of the composite beams;
- Evidence on cracking patterns and modes of rupture of the models tested;
- and conclusions about the resistance of the respective connections.

It should be emphasized that the data were categorized based on the similarity of studies, that is, to explore them in the search for consistent patterns or systematic relationships between variables.

Also, the primary data and characteristics of the scientific strategy of the selected studies will be presented as a bibliometric analysis, which consists of the application of statistical and mathematical methods to analyze and construct indicators on the dynamics and evolution of scientific and technological information on the given topic.

2.1.5 Outcome measure

In this stage, the results concerning the previously defined parameters regarding the Composite beam flexural tests performed by the respective selected works were qualitatively evaluated. In this way, it was assessed the evidence that deals with maximum load capacity, ductility parameters such as load-slip and load-uplift curves, and cracking characteristics of the

[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.

respective models. In this sense, were tried to synthesize the evidence to answer the desired scientific question presented in 2.1.1.

2.2 RESULTS AND DISCUSSION

The initial search without filtering the subject area to engineering recorded 2123 studies in the database, but then, still in the database, with the subject area filter applied, it was recorded 1936. In which, 1739 documents were recorded in research 1, 32 papers in research 2, 348 in research 3, and 04 in research 4, with the researches as described in Table 1. By title and abstract, 434 studies potentially relevant to the SR were selected. After that, the duplicated records from different researches were removed, and finally, 415 studies remained. Therefore, those studies were evaluated according to the eligibility criteria. Twelve articles, in the end, met the inclusion criteria and were added to the SR, to be analyzed carefully. Figure 11 presents the flow diagram of studies search, and Table 3 describes the results.

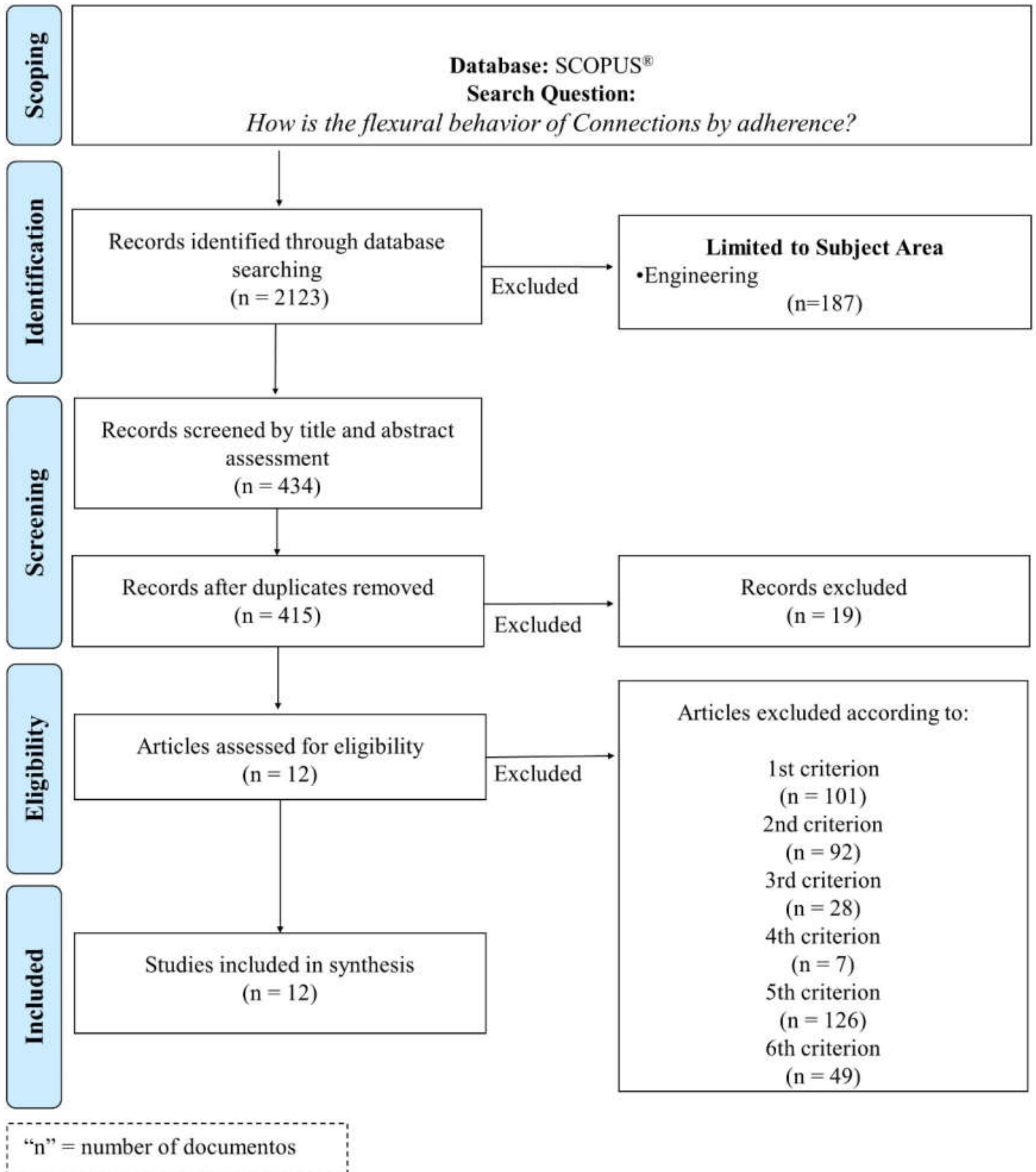


Figure 11. Flowchart of the systematic review process (PRISMA flow diagram).

Table 3 - Selected Studies

Citation	Title
Alves *et al.*, 2018	Prospective study on the behaviour of composite beams with an indented shear connector.
Diógenes *et al.*, 2018	Tests on composite beams using new connections by adherence.
Dudziński *et al.*, 2011	Study on fatigue cracks in steel-concrete shear connection with composite dowels.
Harnatkiewicz *et al.*, 2011	Research on fatigue cracks in composite dowel shear connection.
Jeong *et al.*, 2009	Longitudinal shear resistance of steel-concrete composite slabs with perfobond shear connectors.
Kim and Jeong, 2006	Experimental investigation on behaviour of steel-concrete composite bridge decks with perfobond ribs.
Kim *et al.*, 2014	Behavior of composite girder with Y-type perfobond rib shear connectors.
Kożuch and Lorenc, 2019	Stress concentration factors of shear connection by composite dowels with MCL shape.
Li *et al.*, 2012	Experimental study on the bend and shear behaviors of steel-concrete composite beams with notched web of inverted T-shaped steel section.
Papastergiou and Lebet, 2011	New steel-concrete connection for prefabricated composite bridges.
Papastergiou and Lebet, 2014	Design and experimental verification of an innovative steel-concrete composite beam.
Thomann and Lebet, 2008	A mechanical model for connections by adherence for steel-concrete composite beams.

2.2.1 Bibliometric analysis

It is essential to see the bibliometric indicators in the subject since it helps to measure indices of production and dissemination of knowledge, that allows following the own development of the scientific discipline, as well as the standards of authorship, publication, and use of research results.

Figure 12 shows the annual distribution of included studies from 2005 to 2020. Even though the research was made without a limit for the paper publication date, after the exclusion criteria's in this SR, there were no papers on the subject before 2006, which can be because the study of connections by adherence is relatively new. However, after 2006, there are publications in more than 60% of the period showed in Figure 12, which indicates the growing demand for knowledge in this subject.

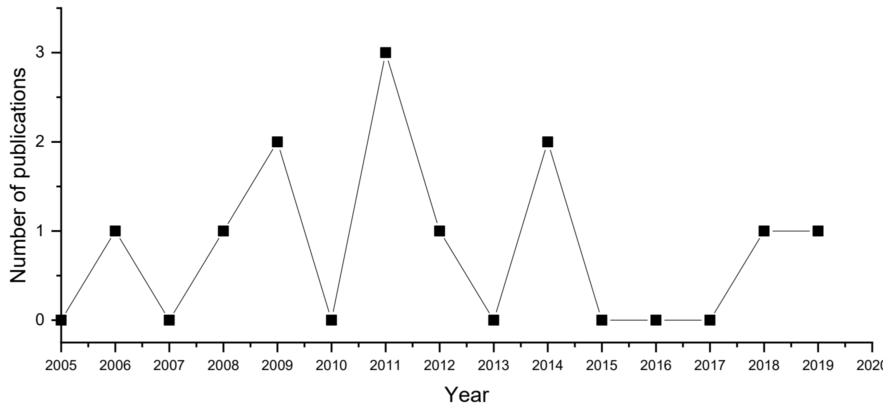


Figure 12 - Annual distribution of publications.

The journals and their attendance, referring to the study publications, are presented together with last year's SJR (SCImago Journal Rank) and IF (impact factor) indicators in Table 4. Both indicators assist classifying the performance and impact of scientific journals and are often used to rank them according to relevance in their field.

Among these journals, as can be seen in Table 4, none had a majority in the two ranks, simultaneously, but the difference can be noted between the Journal of Constructional Steel Research, Archives of Civil and Mechanical Engineering, Engineering Failure Analysis, Engineering Structures and the other ones, where the cited one had higher indexes.

From this perspective, 70% of the studies can be considered of high relevance. Five of them published in the JCSR (Table 4).

Table 4 – Journals covered.

Journal	Quantity	SJR	IF
Journal of Constructional Steel Research (JCSR)	5	1.719	2.650
Archives of Civil And Mechanical Engineering (ACME)	2	0.846	2.846
Engineering Failure Analysis (EFA)	1	0.931	2.203
Engineering Structures (ES)	1	1.628	3.345
International Journal of Steel Structures (IJSS)	1	0.445	0.873
Proceedings of The Institution of Civil Engineers - Structures and Buildings (PICE)	1	0.501	0.877
Stahlbau (S)	1	0.265	0.404

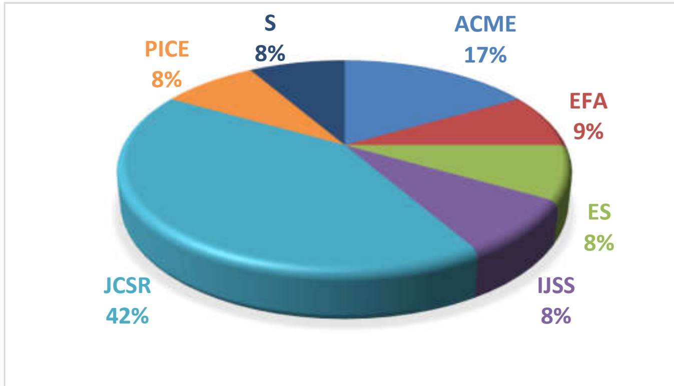


Figure 13 - Frequency of journals.

Table 5 shows the 9 highest number of author citations and the respective authors. It was showed just the top 9 because there was a lot author with only four citations. When it is considered all the authors of each article, it is observed a significant amount of citation for the author Lorenc, W. with 41 citations followed by Seidl, G. with 23 citations. The highlighted authors in Table 5 are the one with selected works in this RS, that represents almost half of the most cited authors, indicating that this work includes a significant area of the scientific knowledge of its subject.

Table 5 - Top 10 number of author citations

Position	Qty of citations	Author
1st	41	Lorenc, W.
2nd	23	Seidl, G.
3rd	20	Kożuch, M.
4th	13	Lebet, J. P.
5th	10	Berthellemy, J Rowiński, S.
6th	9	Thomann, M. Kubica, E. Hechler, O
7th	8	Cruz, P.J.S. Hosain. M.U. Valente, M. I. B.
8th	6	Viefhues, E. Hegger, J. Oguejiofor, E.C. Papastergiou, D.
9th	5	Li, G Li, X Rauscher, S

Table 6 presents the top 7 most cited references, distributed in alphabetical order among those with the same number of citations. The number of seven references was due to the ones with just two citations were too big, so it was considered only the references with three or more citations.

It can be seen in Table 6 that none reference was selected in this RS, but that can be explained because two of the texts were Ph.D. dissertation that even though were excluded by the exclusion criteria, some papers that were developed by those works were added in this research. And the other ones that were not selected do not present a flexural test that is the focus of this work, even though they discuss about linear connectors.

Table 6 – Top 10 most cited references.

Position	**Qty of citations**	**Reference**
1st	4	Seidl, G. Behaviour and load capacity of composite dowels in steel-concrete composite girders. Report PRE no. 4/ 2009 (Ph.D. dissertation), Wroclaw University of Technology, 2009.
2nd	4	Oguejiofor, E.C.; Hosain, M. U.A parametric study of Perfobond rib shear connectors. Canadian Journal of Civil Engineering 21(4): 614-625, 1994.
3rd	4	Thomann, M. Connexions par adherence pour les ponts mextes acier-béton. EPFL Thèse No 3381. Ecole Polytechnique Fédéreal de Lausanne. Switzerland, 2005.
4th	3	Lorenc, W.; Ignatowicz; Kubic, E.; Seidl, G. Numerical Model of Shear Connection By Concrete Dowels, Recent Developments in Structural Engineering Mechanics and Computation, Mill Press, Rotterdam, Netherlands, 2007.
5th	3	Hechler, O.; Lorenc, W.; Seidl, G.; Viefhues, E. Continuous shear connectors in bridge construction, Composite Construction VI conference, USA, Colorado, 2008.
6th	3	Valente, I.; Cruz, P. J. Experimental analysis of perfobond shear connection between steel and lightweight concrete. Journal of Constructional Steel Research 60(3–5): 465–479, 2004.
7th	3	Lorenc, W.; Kubica, E.; Kożuch, M. Testing procedures in evaluation of resistance of innovative shear connection with composite dowels, Arch. Civil Mech. Eng. 10 (3) 51–63, 2010.

2.2.2 Study characterization

In selected studies, there are a lot of differences in the type of connection, connector use, the focus of the connection, etc. So in Table 7, there is an overview of the selected studies.

Regarding the focus of the application for the new connections of each study, it was divided into three different groups: bridge construction, building construction, and general application. From the total, 67%, 8%, and 25% of studies are in the first, second, and third groups, respectively. One should note that when the investigation focus is "general", some information may be valid for both bridge and building constructions. The high number of works focusing on bridge construction shows that the linear connectors have as their principal function the use in bridges, even though there are some studies with different focus.

The studied behavior also had some variation in these studies, almost all of them had studied the static behavior, even though static tests give great information, it also necessary to consider the cyclic behavior of those structures, since these connections, as mentioned before, have primary utilization in bridges, so some studies did some tests with cyclic loads.

In relation to the cementitious material used in the prototypes, almost for all studies was only used conventional concrete, but in those with connections by adherence, there was the use of High-Performance Mortar (HPM) in Diógenes *et al.* (2018) and High Strength Cement Grout (HSCG) in Papastergiou and Lebet (2011), Papastergiou and Lebet (2014) and Thomann and Lebet (2008). The last four cited works were also the only ones with the use of precast slabs, showing that connection by adherence has a good relation with pre-fabrication.

Even though there are four works with connections by adherence, they have differences in how the connections were achieved, but in particular, for the works of Papastergiou and Lebet (2011) and Papastergiou and Lebet (2014), it is talking about the same experiment. However, in the last two studies, some discussions are different, so It was selected the two papers not to let pass any relevant information about this connection.

For other types of connectors, there are two types, Puzzle shape (PZ connector) and Clothoidal Shape (CL connector). Those connectors were studied in the same Project named PreCo-Beam. The connection is made with the cut in the half of a rolled I-beam, in that way two T-sections are created, depend on how this cut is done, it will have a Puzzle or a Clothoidal shape. For the connection, the shaped part of the beam will be surrounded with concrete obtaining an interaction by composite dowels of concrete.

Another type of connector that follows the same way of the PZ and CL connector, but it not from the PreCo-Beam project, is the trapezoid connector proposed by Li *et al.* (2012), that is formed by the cut in the half of an H-shaped beam to create two T shaped beam, but now with a trapezoid shape.

Jeong *et al.* (2009) and Kim and Jeong (2006) study the connection obtained by a perforbond connector with a steel deck profile. And in Kim *et al.* (2014) was analyzed the use of a Y-perfobond that is a variation of the Perfobond connector, that instead of being just a flat plate, in this one there is angled parts in the top part of the connector. In that work, it also had experiments with stud type connectors but only for comparison since it was not the focus of the paper.

The interfaces are related to how stresses are transmitted. Most of the studies only have the interfaces connecting the conventional concrete to the connector or the steel profile, being it a steel deck, an H beam, I beam or a T-shape beam. However, in those with connections by adherence had the use of different materials such as HSCG or HPM, i. e., new interfaces were produced, as shown in Table 7. This fact is directly related to the investigation objective, evaluate the use of precast concrete slabs. Furthermore, it is known that the structural connection behavior is, indeed, assessed by the behavior of the interfaces formed by the materials which composes the connection

Table 7. Overview of included studies.

Ref.	**Application**	**Studied behavior**	**Cementitious material**	**Connector type**	**Slab type**	**Interfaces**	**Connection**
Alves *et al.*, 2018	General	Static	CC	CR	Cast-in-place	1 and 2	Figure 14 (a)
Diógenes *et al.*, 2018	Building	Static	CC and HPM	Adherence	Cast-in-place and precast	1,2,3,4 and 5	Figure 14 (b)
Dudziński *et al.*, 2011	Bridge	Dynamic	CC	PZ	Cast-in-place	1 and 2	Figure 14 (c)
Harnatkiewicz *et al.*, 2011	Bridge	Dynamic	CC	PZ	Cast-in-place	1 and 2	Figure 14 (d)
Jeong, Kim and Koo, 2009	Bridge	Static	CC	PBL	Cast-in-place	1 and 2	Figure 14 (e)
Kim and Jeong, 2006	Bridge	Static	CC	PBL	Cast-in-place	1 and 2	Figure 14 (f)
Kim *et al.*, 2014	General	Static	CC	Y-PBL and stud	Cast-in-place	1 and 2	Figure 14 (g)
Kożuch and Lorenc, 2019	Bridge	Dynamic and Static	CC	CL	Cast-in-place	1 and 2	Figure 14 (h)
Li *et al.*, 2012	General	Static	CC	Trapezoid	Cast-in-place	1 and 2	Figure 14 (i)
Papastergiou and Lebet, 2011	Bridge	Dynamic and Static	CC and HSCG	Adherence	Precast	6, 7 and 8	Figure 14 (j)
Papastergiou and Lebet, 2014	Bridge	Dynamic and Static	CC and HSCG	Adherence	Precast	6, 7 and 8	Figure 14 (j)
Thomann and Lebet, 2008	Bridge	Static	CC and HSCG	Adherence	Precast	6, 7 and 8	Figure 14 (h)

Notes:		**Types of interfaces**
CC	Conventional Concrete	1. Connector-Concrete
CR	Crestbond	2. Steel profile-Concrete
PZ	Puzzle shape	3. Connector-HPM
PBL	Perfobond	4. Concrete-HPM
CL	Clothoidal Shape	5. Steel profile-HPM
Y-PBL	Y-Perfobond	6. Concrete-HSCG
HPM	High-performance Mortar	7. HSCG-connector
HSCG	High strength cement grout	8. Steel Profile-HSCG

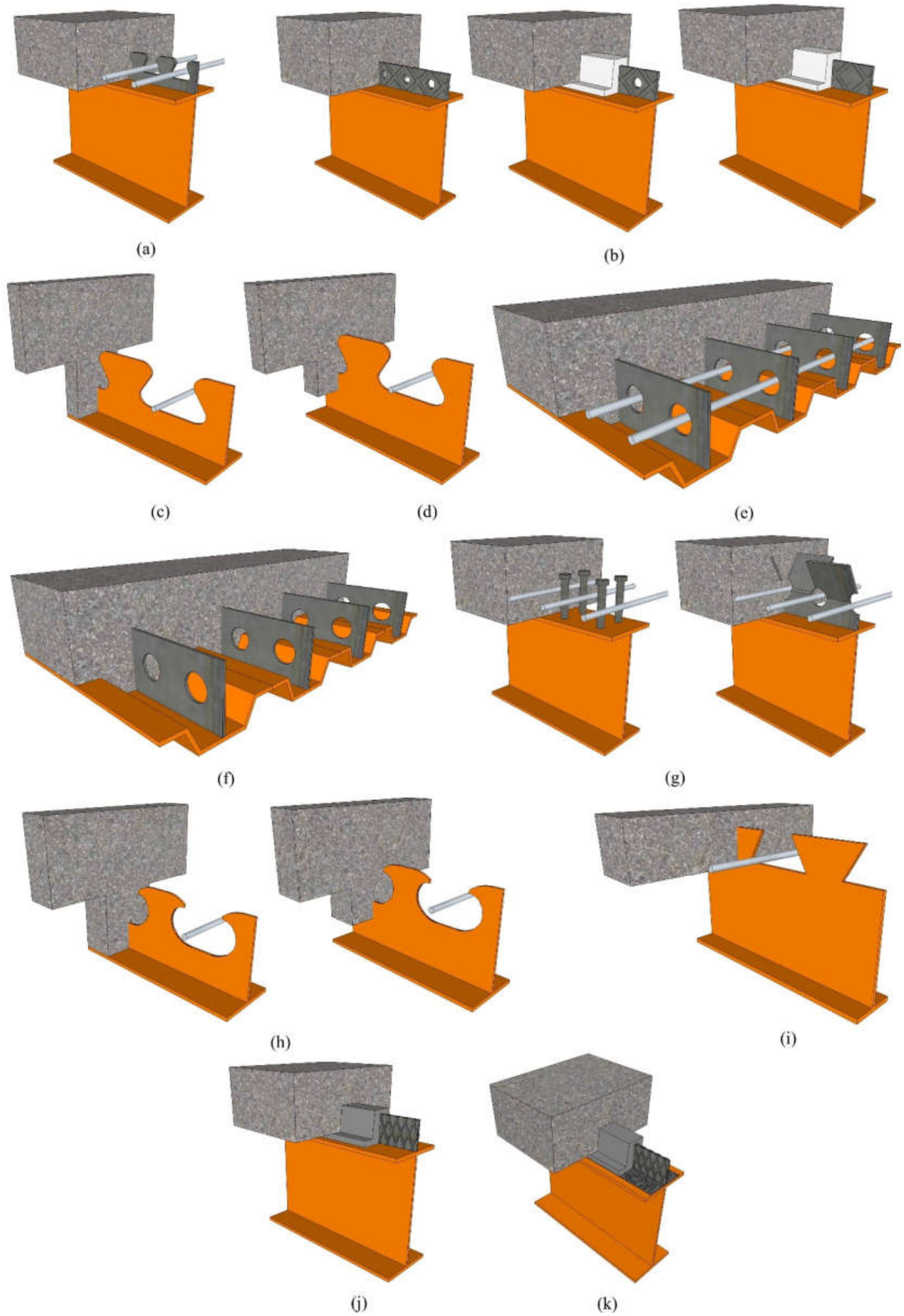


Figure 14 - Studied connections by Alves et al., 2018 (a); Diógenes et al., 2018 (b); Dudziński et al., 2011 (c); Harnatkiewicz et al., 2011 (d); Jeong et al., 2009 (e); Kim and Jeong, 2006 (f); Kim et al., 2014 (g); Kożuch and Lorenc, 2019 (h); Li et al., 2012 (i); Papastergiou and Lebet, 2011, and Papastergiou and Lebet, 2014 (j); Thomann and Lebet, 2008 (k).

As a methodological strategy, all other studies presented some variation in the experimental setup, either referring to geometry, load type, connector type, among others. Rationally, those differences are made in other to attend the aims of each work. To better understand the variations in the layout and the primary objective of the paper, in Table 8, there is the Main characteristics of methodology.

The strength class of concrete has been divided into two groups according to (European Committee for Standardization., 2004): Conventional and High Strength Concrete to simplify the comparison among the studies. The first group includes the concrete classes C20 to C50, while higher classes (> C55) are part of the second group. Thus, six studies (50%) performed tests using conventional concrete (Alves *et al.* (2018), Diógenes *et al.* (2018), Jeong *et al.* (2009), Kim and Jeong (2006), Kim *et al.* (2014), and Li *et al.* (2012), while three studies (25%) used high-strength concrete (Kożuch and Lorenc, 2019 Papastergiou and Lebet, 2011 Papastergiou and Lebet, 2014) (Table 7).

For all studies, it was used a conventional composition of the concrete (no additions), and the density of concrete was normal for all specimens.

Other characteristics and methodological strategies are discussed here to support the discussion presented in the section (Table 8). The type of load and the method of application – displacement control or load control, there was a pattern that for all cyclic load, it was used Load control, and for all monotonic tests (static tests) it was used Displacement control. The control used during the tests is an important factor that can give precision of the load-displacement curves obtained in all stages of test: pre-failure, failure, and post-failure behavior.

Table 8. Main characteristics of methodology.

Ref.	Nº of models	Setup description	Justification	Loading Type	Concrete Strength (MPa)	Connector f_y (MPa)
Alves *et al.*, 2018	2	Simply supported composite beam with 3 m span, with a CR connector in the top flange of steel beam, analyzed by flexural tests and numerical study.	To complement the knowledge of the CR connector with new experimental tests performed on composite beams.	Monotonic/ DC	38.13–39.15 (a)	282,41 (a)
Diógenes *et al.*, 2018	6	Simply supported composite beam with 3.3 m span, changing the types of connectors by adherence with and without holes, and different types of slab, Cast-in-place, and precast.	To contribute to the study of connections by adherence proposing new types of patterns in the connection and the use of this connection in precast slabs.	Monotonic/ DC	37.60 (a) 94.00(e)	329,60 (a)
Dudziński *et al.*, 2011	1	Simply supported Composite beam with 3.6 m span, subjected to a fatigue test, where the concrete is connected to a cut steel beam in PZ shape.	To study the behavior of a composite beam using half of an I profile cut in PZ shape.	Cyclic/LC	NI	NI
Harnatkiewicz *et al.*, 2011	1	A four-point fatigue test of a composite slab with a connector steel dowel was conducted, with a span length of 3.6 m, to study fatigue cracks of the connector in tests cyclic loads.	To study an approach to estimating the fatigue resistance of composite dowels, focusing on a description of stress analysis in steel dowels, and the impact of the manufacturing method on fatigue lifespan.	LC	NI	NI
Jeong *et al.*, 2009	16	Simply supported full-scale composite slabs formed by a steel deck connected by a PBL, Having two different span lengths of 3.5 and 2.5 m with four-point flexural test varying the shear span and reinforcement through the connector.	Aim to evaluate the longitudinal shear resistance using the m-k method for a steel-concrete composite bridge.	Monotonic/DC	30.00 (d)	368,00 (a)
Kim and Jeong, 2006	9	Four-point flexural test of composite slabs formed by a steel deck connected by a PBL, with span length of 3.5 m varying the type of steel deck used and no reinforcement is used through the connector.	Aim to assess the usability of PBL for composite bridge decks with profiled steel sheeting and application of the proposed deck system for a bridge.	Monotonic/DC	35.10 (a)	368,00 (a)
Kim *et al.*, 2014	1	A three-point bending test of a composite slab with connector Y-type Perfobond and other with stud connector were conducted, with a span length of 5,0 m.	To provide an analytical model of the proposed Y-type perfobond rib shear connector in a composite girder considering the partial composite behavior is developed to evaluate the structural behaviors of the girder.	LC	31.8–32.0 (a)	NI
Kożuch and Lorenc, 2019	3	Four-point flexural test of composite slabs with a connected by CL shape composite dowel, with a span length of 4.85 m. Connectors in the vicinity of the point in which loads were applied were clad in foamed polystyrene to eliminate local perturbations.	Studies to the evaluation of the elastic resistance of the steel part of a continuous shear connection named CL shape for the application in bridge engineering, with attention was paid to fatigue resistance and, therefore, also to the need to determine the state of stresses in the connector.	DC and LC	74.20 (a)	443,00 (a)

Table 8 (Continued)

Li *et al.*, 2012	6	Four-point flexural test of composite slabs with notched web of inverted T-shaped steel section, with a span length of 2,88 m varying the local of application Loads.	To identify the bending behavior of the composite beam with a notched web of inverted T-shaped steel section and the factors affecting the bending behavior of the composite beam, including the cubic compressive strength of concrete, the height of the composite beam, the size of trapezoid connector and reinforcement rate is considered.	DC	24.4-30.9 (a)	300.00-312.00 (a)
Papastergiou and Lebet, 2011	1	Simply supported composite beam connected by adherence to a prefabricated slab with a length span of 9 m, first submitted to a cyclic test, then to a static test. The gap between the elements is filled with high strength cement grout.	To simulate the behavior of the new steel-concrete connection with prefabricated concrete slab.	Monotonic and Cyclic/DC and LC	56.70 (a)	NI
Papastergiou and Lebet, 2014	1	Simply supported composite beam connected by adherence to a prefabricated slab with a length span of 9 m, first submitted to a static and fatigue loading. The gap between the elements is filled with high strength cement grout.	To study of design method and the experimental verification of a new type of steel-concrete composite beam with a prefabricated concrete slab under static and fatigue loading.	DC and LC	56.70 (a)	NI
Thomann and Lebet, 2008	6	Simple supported steel-concrete composite beams connected by adherence to a prefabricated slab and with the gap between the elements is filled with high strength cement grout, spanning 4–8 m, were tested to study the failure mechanism and the distribution of shear flow in the steel-concrete interface.	To analyze a new steel-concrete shear connection with prefabricated concrete slab, known as connections by adherence, whose resistance is due to friction between various interfaces.	DC	NI	NI

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

2.2.3 Discussion

Even though the studies with composites beam reviewed in this work show considerable differences between each other as materials properties, different spans, the geometry of the structure, type of loading, etc. In this part, it will be discussed some of the principal characteristics of this analyzed works.

2.2.3.1 Load and vertical displacement

One of the essential characteristics of Structures subjected to flexural action is load-displacement behavior because that can provide a better understanding of how the structure will respond to the load. In the works of Alves *et al.* (2018), Diógenes *et al.* (2018), Jeong *et al.* (2009), Kim and Jeong (2006), Kim *et al.* (2014), Li *et al.* (2012), Papastergiou and Lebet (2011), Papastergiou and Lebet (2014), and Thomann and Lebet (2008), the load-displacement graph is provided. With so many types of connections, geometry, and proprieties of materials, it is challenging to compare the displacement of the studied specimens directly.

However, it can be seen some similarities in the load-displacement behavior. At first, for all studies, there is a linear behavior that covers almost the whole test. After that, it observed a constant drop in the inclination of the curve. For connections by adherence, (Diógenes *et al.* (2018), Papastergiou and Lebet (2011), Papastergiou and Lebet (2014) and Thomann and Lebet (2008)) after this drop of inclination, it is observed a sudden loss in the capacity of the beam, representing the rupture of the connection between the connector and the concrete. And for the rest of the test, the curves go horizontally, representing the plastification of the composite beam.

The same behavior, as for connections by adherence, was observed for Crestbond connection (Alves *et al.*, 2018). For Kim *et al.* (2014), where is used Y-perfobond and stud connector, it is not observed a sudden loss in the capacity of the composite beam, i. e., the curve initially has a positive inclination and then slowly goes to a horizontal line. The same behavior in Kim *et al.* (2014) is observed in Li *et al.* (2012), where is used a trapezoid connector.

It is used perfobond connectors with or without reinforcements through the holes In Jeong *et al.* (2009) and Kim and Jeong (2006), respectively. The behavior is a little different, the curve goes through a positive inclination to a negative vary fast, unfortunately it is not possible to see if, after this drop in the inclination os the curve, the curve would go horizontally, because it seems the author stopped the test right after this change in the rigidity of the composite structure.

2.2.3.2 Slip and Uplift

Many authors highlight the importance of studying slip and uplift that arise as shear connectors do not provide a perfect connection, resulting in the relative slip between materials.

Alves *et al.* (2018), Diógenes *et al.* (2018), Jeong *et al.* (2009), Kim and Jeong (2006), Kim *et al.* (2014), Li *et al.* (2012), Papastergiou and Lebet (2011), Papastergiou and Lebet (2014), and Thomann and Lebet (2008) discussed about slip results. However, only Diógenes *et al.* (2018) and Alves *et al.* (2018) presented details about uplift in their results.

Alves *et al.* (2018) showed, in the bending moment test, that the composite beams with CR connector showed minimal slip values, indicating that the connector used has high rigidity and provides a high degree of interaction between the steel and concrete sections. The same is true for uplift values, proving that the CR connector is very effective at preventing the uplift effect.

Kim *et al.* (2014) compared the results from Y-PBL with the Stud connector. Their experimental and numerical results show that under the same loading conditions, the Y-type perfobond had a higher stiffness relative to relative slip when compared to the Stud connector, indicating that the Y-type perfobond connector increased the composite beam interaction and, consequently, the load capacity of the composite beam.

The trapezoid connector from Li *et al.* (2012) shows in its behavior that loads between 20% and 40% of the ultimate load (P_u) do not cause any slip. When the load reaches 40% to 60% of P_u, a slight slip is observed. However, there is no appearance of cracks in the sample, which indicates that the sample remains in the elastic state. When reaching loads above 70%, there is an increase of slip and the appearance of longitudinal cracks in the concrete slab.

Diógenes *et al.* (2018) used connectors by adherence, type R and type RP. Their results showed that both connectors presented resistant capacity even after composite beam plasticization. However, it was not possible to detect a significant influence on the slip evolution about the connector variation. The research also used two types of slabs, cast-in-place and precast. Samples with slab cast-in-place showed higher rigidity and, consequently, less slip than precast slabs, indicating a higher interaction between the steel beam and the concrete slab in the first case. Regarding uplift, all models did not present values above 0.5 mm.

According to the same author, this was due to the action of the slab's weight and the direction of load application, which promoted an increase in the stiffness of the composite action in the beams, in comparison with push-out tests.

Also, using adherence connectors, Papastergiou and Lebet (2011), and Papastergiou and Lebet (2014) performed a fatigue test and studied the influence of cyclic loading on slip during the test and residual slip after it. Subsequently, a static test was performed to verify the impact of the fatigue test on the final capacity of the composite beam. The results showed that in the fatigue test, the residual slip increases with repeated loading. However, after one million cycles, the increase in residual slip tends to be limited. In the static test, slip at failure developed only at one end of the beam and only after complete section plasticization. Despite the residual slip in fatigue tests, those tests have little influence on the resistant shear capacity of the composite beam.

In the same line as the adherence connectors, Thomann and Lebet (2008) show that during the test, a large peak in slip distribution was measured when the bending moment exceeded the resilient elastic moment of the composite beam. The author states that this is due to the emergence of a shear flow peak that must always remain below the shear strength so that no brittle composite beam failure occurs.

Finally, Kim and Jeong (2006) and Jeong *et al.* (2009) presented the perfobond rib shear connector. The flexural tests performed by Jeong *et al.* (2009) showed that, for this connector, the larger the span analyzed, the higher the slip, which for the tested samples presented an end-slip ranging from 0.4 to 1.1 mm. In turn, Kim and Jeong (2006) showed that in the elastic phase, the slip measured in the samples was almost zero. Their results indicated that the behavior of the composite deck could be defined as ductile.

2.2.3.3 Fatigue behavior

As seen in Table 7, most of the studies for straight connectors are designed for bridge application, so for this use, the knowledge about the cyclic behavior of this structure is essential since the load applied in the real structure is cyclic as well. However, just in Dudziński *et al.* (2011), Harnatkiewicz *et al.* (2011), Papastergiou and Lebet (2011), and Papastergiou and Lebet (2014), it is present fatigue test, where the last two cited discuss about the same experiment, and in Kożuch and Lorenc (2019), it is performed tests with cyclic loads but just 25 times that does not make a significant difference in the static tests that were done later.

Regarding the behavior observed in those studies, there was a complete failure due the cyclic load in Dudziński *et al.* (2011) and Harnatkiewicz *et al.* (2011), it was the intention of the authors to go until failure, but one should note that there were considered cracking even in the steel profile. However, in the work of Papastergiou and Lebet (2011), and Papastergiou and

Lebet (2014), where the maximum value of the loads applied reached approximately 82% of the ultimate load obtained in the static test.

For the same last two works cited, after five million cycles since the accumulated slip had stabilized, there was only a minor influence for the overall bending performance of the beam with a little change in the elastic neutral axis of the beam. So it can be seen that connections by adherence have an enhanced fatigue resistance since those connections were primarily designed for bridge uses.

It is note-worth that in the works of Dudziński *et al.* (2011), Harnatkiewicz *et al.* (2011), there is an emphasis on how the profiles are cut since, in those studies, the steel profile is also the connector formed through the cut in the middle resulting in two T beams. Depending on the technique that was used in the cut – plasma, gas, or water – the resistance for fatigue, a difference from the connectors used in adherence connectors that don't show this relation.

2.2.3.4 Cracking patterns and failure model

To know better the structural behavior of the structures, one must pay attention to the failure modes and cracking patterns that may occur, so it is essential to identify those characteristics from the composite beam using straight connectors. According to Jeong *et al.* (2009), the failure mode is related to the longitudinal shear resistance of the specimen. Thus this information can help us do understand how is the level of interaction between the two elements.

This rupture can be fragile or ductile, and those different behaviors may ask different provisions for preventing failure. Also cracking pattern that usually occurs before the rupture of the structures helps to know how close to the failure is the structure and what will factor will lead to rupture.

According to the review studies, the main failures can be conditioned by concrete crushing, cracking of the concrete or the steel beam, Plastification of the steel beam (Table 9). So it is interesting to see what causes different types of failures in linear connections. With that said, it is in your interest to make the following points:

a) Only two studies showed cracks in the steel profile (Dudziński *et al.*, 2011; Harnatkiewicz *et al.*, 2011). Besides the cracking in the steel, there was concrete cracking in the lower part. The two studies used the same type of connection, PZ shape. The different behavior in those two studies concerning other studies is because the specimens were submitted to fatigue tests until failure. Besides, in those studies, as mentioned before, has as steel profile a T beam, in other studies which had also fatigue tests had profiles with lower and upper flange and did not show cracking in the beam. Also, with the help of numerical models, it was possible to see cracks in the middle of the concrete a lot before the rupture.

b) Four studies selected in this work presented as their primary mode of rupture of composite beams the rupture of concrete slabs (Alves *et al.*, 2018; Kim *et al.*, 2014; Kożuch and Lorenc, 2019; Thomann and Lebet, 2008). That shows that even with the rupture of some parts of the concrete, the connection between the two elements is still working. Also though it was not the event that causes the failure of the composite beam, in the studies of Papastergiou and Lebet (2011) and Papastergiou and Lebet (2014), there was also concrete crushing. Almost 50% of the studies showed this behavior, and half of them are connections by adherence, showing those connections can achieve even higher loads with better quality concretes.

c) In six studies there was failure due to the intensive cracking of the bottom part of concrete (Diógenes *et al.*, 2018; Dudziński *et al.*, 2011; Harnatkiewicz *et al.*, 2011; Jeong *et al.*, 2009; Kim and Jeong, 2006; Li *et al.*, 2012). That kind of rupture is not just related with just resistance of the connection, because when concrete starts do crack near the interface connector-concrete, the interaction between those elements starts to fail, as well as the shear resistance starts to decrease. The case described is likely what happened in Diógenes *et al.* (2018) and in part of the experiments in Li *et al.* (2012), because in other tests in the same work there were differences in the shear span that provoked cracks from more significant shear stress, the same as in Jeong *et al.* (2009), and Kim and Jeong (2006).

d) In the studies Papastergiou and Lebet (2011) and Papastergiou and Lebet (2014), the authors talk about the same experiment. This experiment had as principal cause of failure the plastification of the steel beam, which shows that the connection by adherence in this study provided an excellent interaction between the two elements, indicating that the concrete had practically only compression with continuity in the stresses, with steel in tension.

e) Even though in other studies with different tests (Push-out tests) with connection by adherence indicated that those connections had a fragile rupture (Diógenes *et al.*, 2015). There were differences in the behavior of those connections in the studied works. In Diógenes *et al.*, 2018, only the cast-in-place slabs showed this behavior, and in Thomann and Lebet, 2008, the same was observed, but in Papastergiou and Lebet, 2011 a ductile behavior was observed. The work that for all specimens presented a fragile behavior other than the one cited before is Alves *et al.*, 2018, with the CR connector, the last ones had differences depending on the shear span or different types of steel profiles.

Table 9. Main failure mode.

Ref.	Main failure mode
Alves *et al.*, 2018	Concrete crushing in the upper part of the slab and high vertical deflection.
Diógenes *et al.*, 2018	Significant cracking in the lower part of concrete with steel beam plastification.
Dudziński *et al.*, 2011	Cracking in the lower part of the concrete and the steel beam.
Harnatkiewicz *et al.*, 2011	Fatigue cracks in steel beam and concrete.
Jeong *et al.*, 2009	Significant cracking.
Kim and Jeong, 2006	Significant cracking.
Kim *et al.*, 2014	Concrete crushing in the upper part of the slab.
Kożuch and Lorenc, 2019	Brittle fracture of the reinforced concrete slab at the top.
Li *et al.*, 2012	Concrete shear rupture between the support and the application load point or significant cracking.
Papastergiou and Lebet, 2011	Plastification of the steel beam.
Papastergiou and Lebet, 2014	Plastification of the steel beam.
Thomann and Lebet, 2008	Concrete crushing.

Therefore, it is understood that the composite connection from straight connectors has its limit of rupture usually governed by the rupture of concrete slabs and sometimes show fragile behavior when the rupture occurs in the connections. That indicates that connections with straight connectors provide good interaction between two elements, but the interaction also depends on the characteristics of each element separated.

2.2.3.5 Level of interaction

It is difficult to evaluate the maximum load for different composite structures since different materials and geometry are used, so here the maximum load obtained is normalized by the maximum load that would be obtained if considered full interaction between the concrete and the steel, this ratio will be called level of interaction here.

In Alves *et al.* (2018), The bending strength resulted in a value of 152.0 kN.m, which corresponds to a maximum load value of 253.3 kN, with calculations based on Eurocode 4 (2004) and Eurocode 2 (2004). But this value was surpassed during the experimental tests, with a maximum load of 284.7 kN, i. e., a level of interaction 112 %, of course, the maximum of this ratio should be 100 %, but depending on calculation and variability of materials, could reach higher values. But with this value, one must say that with this connector, it can reach a full shear connection.

For all studies with connections by adherence (Diógenes *et al.* (2018), Papastergiou and Lebet (2011), Papastergiou and Lebet (2014) and Thomann and Lebet (2008)), it was reached full shear connection, with a level of interaction a little bit greater than 100 %. Only in some specimens from Diógenes *et al.* (2018), it was not possible to reach this full connection in precast slabs, which can be because the rupture occurred in the interface of HPM and concrete, so that interface is weaker than the connection with the steel connector.

In Kim *et al.* (2014), there is a comparison between the level of interaction that could be obtained with stud or Y-perfobond connectors confronted with results from numerical simulation. The levels of interaction obtained were 80.8% and 82.4% for Stud and Y-PBL connectors, respectively.

For other authors studied in this work, there is not compared values of maximum strength, and some of those could not be calculated by simple normative calculations due to their different geometries as T shaped steel beam with different cut patterns.

2.2.3.6 Longitudinal shear resistance

In studies of steel-concrete composite beams, the importance of determining the longitudinal shear resistance that develops from the degree of interaction between the concrete and the shear connector is highlighted only in Jeong *et al.* (2009). Those authors point out that this resistance influences the structural performance, stiffness, and failure mode of the composite element.

It was possible to empirically calculate the longitudinal shear resistance values of the composite beam with the results from the flexural tests. From the values calculated by the m-k method, when the load was applied in the center of the span, the value of the longitudinal shear resistance averaged 0.88 N / mm², equal to the value found in the push-out tests also performed by the authors.

However, in the same study, it was observed that as the load application approaches the supports, the greater the value of longitudinal shear resistance when compared to push-out tests, overestimating the value of resistance. According to the author, this may have occurred because the frictional force increases with the increase of the normal force acting on the interface. Finally, it is concluded that to determine the value of longitudinal shear strength accurately, sufficient span lengths should be used so that frictional forces are not significant in influencing this strength, and it is advisable to use a relationship between span and load application equal to 3.

2.3 CONCLUSIONS

In this study, a systematic review was performed to propose a new discussion about the flexural behavior of connections by adherence, since the study about that type of connections is relatively new, this work covered all straight connectors to make a comparison between those connectors. Even though there is a lot of studies about linear connectors, only 12 were selected by the exclusion criteria, probably due to the fact of its high cost.

For this, a bibliometric analysis of the studies was performed to identify the main ideas of the application of the connectors, as well as the methodological strategies used by the respective authors. Further, it was qualitatively discussed the several characteristics observed in the selected works. Thus, it has as conclusions that:

- The synthesis of the wide range of studies and their respective methodologies allowed a new way of thinking about adherence connection and its flexural behavior.
- For the load-displacement behavior, it is almost equal to all reviewed connections, with a distinct difference, sudden loss of rigidity when the connection is ruptured. So it should be paid attention that those connections should remain in elastic state.
- Regarding the uplift and the slip, the connections by adherence provided small values during almost all tests, showing a high interaction. Only after the ruptures, great slips can be observed.
- As the connections by adherence were primarily developed for bridge uses, the fatigue behavior of those connections is excellent in comparison to other connectors, showing just a small residual slip and displacement in the neutral line axis. However, it did not affect the static results significantly.
- Therefore, it is understood that the composite connection from straight connectors has its limit of rupture usually governed by the rupture of concrete slabs and sometimes show fragile behavior when the rupture occurs in the connections. That indicates that connections with straight connectors provide good interaction between two elements, but the interaction also depends on the characteristics of each element separated.
- Regarding the level of interaction obtained for all connections in this work, it is possible to say that connections by adherence have full shear connection, wherein all studies with

those connections it was possible to reach in the tests the expected ultimate load with full interaction, obtained by normative calculation or numerical calculations.

- In studies of determination of longitudinal shear resistance, it was observed that the relationship between the span length and the load application influence the value of this resistance, being necessary to consider in the bending tests a sufficiently adequate relationship so that the friction forces do not make significant in the influence of the longitudinal shear resistance value.

CHAPTER 3

EXPERIMENTAL PROGRAM

The next sections will describe the flexural tests performed in the LABEME – Laboratory of Tests in Materials and Structures – and Mimee – Lab of Building Information Modeling, Testing, and Modeling of Structures – at the Federal University of Paraiba, Brazil. In this phase, dynamic non-destructive tests were also performed in parallel with the flexural tests, to obtain the vibrational behavior of the prototype in the before and after the static test.

The results and observations made during the tests with the composite beams allowed in this study allowed to study the connection by adherence regarding:

- The level of shear connection on the composite section with distinct types of slab.
- The stiffness, strength, and deformation capacity of the designed connector when included in a composite beam.
- The connection behavior under load applied perpendicular to the concrete slab. The slab self-weight, along with the loads applied perpendicularly, influences the connection strength since the create confinement in the connection region.

3.1 METHODOLOGY

In this research, it was evaluated experimentally only one type of linear connector by adherence originating from the two steel plates welded back to back with grooves in a checkered pattern (Figure 15). The choice of this pattern was made because this type of steel plate is commercially disseminated in Brazil, and from the studies of Sonoda *et al.* (2000) and Chen *et al.* (2018), this distribution of grooves showed a good performance. So this pattern would allow 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 slabs of the ribbed type, characterizing the initial hypothesis of the work.

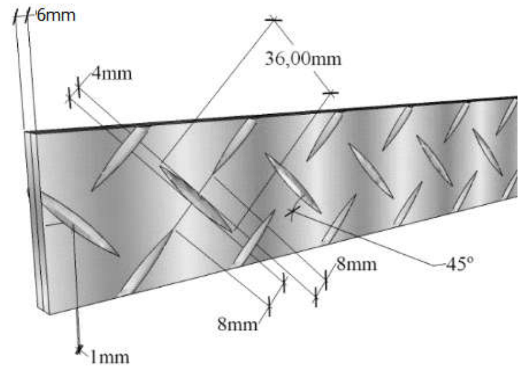


Figure 15 - Linear connector formed by checkered plates welded “back-to-back”.

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

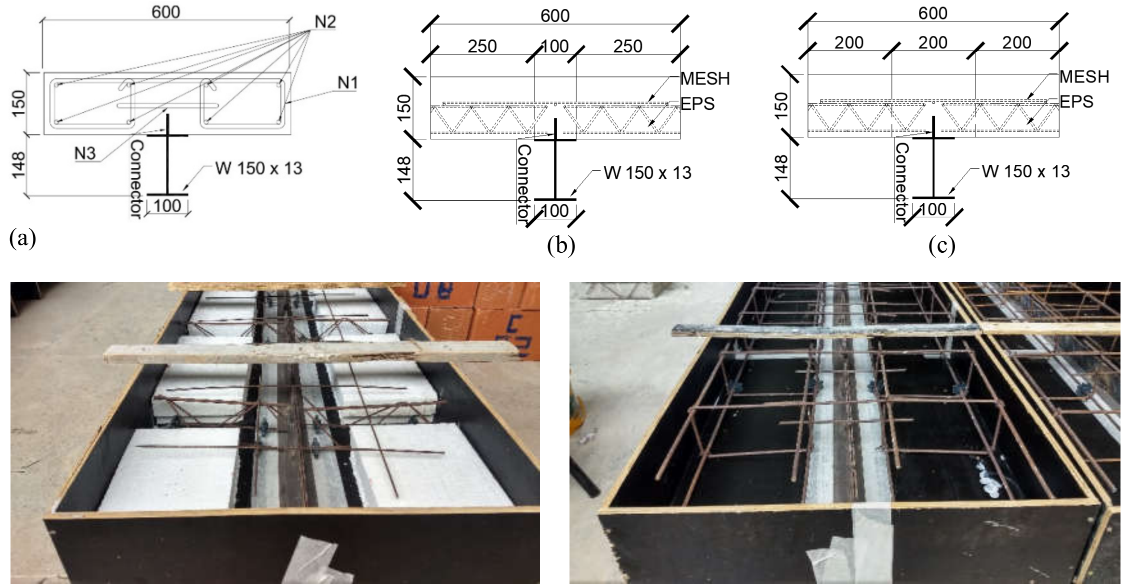
Most of the times this lattice joist is connected to precast concrete slab in its lower part, although it was decided to complete the whole model at a single time with the objective of eliminating a possible problem caused by the presence of a construction joint, since there would initially be concrete with different resistances in the same specimen. Then, the trusses were used as reinforcement in the ribs, and the slabs were cast in loco as a whole.

3.2 SPECIMEN DESCRIPTION

To enable new discussions on a new type of Connection by Adherence about its flexural behavior. Eight full-scale specimens of composite beams were manufactured to carry out the flexural tests and dynamic tests. These consist of a steel beam connected to a reinforced concrete slab using a continuous rib steel connector. The connector is welded longitudinally on the upper flange of the steel beam, which is embedded in the concrete slab during the concreting to ensure the connection between them.

The distinction of the specimens refers to the type of slab, i.e., there is no variation in geometry or physical properties of the straight connector and the steel-based profile. Therefore, changes in the slab type allowed evaluating the behavior of the connection proposed with different dispositions and inertia, providing a comparative perspective of experimental results between specimens. Thus, four samples used solid reinforced concrete slabs named MAC-1, MAC-2, MAC-3, and MAC-4, and four other models used ribbed slabs with different concrete sections named TRE 10-1, TRE 10-2, TRE 20-1, and TRE 20-2. The Cross-sections of the composite beams are shown in Figure 16. The differences between TRE 10 (Figure 16 b) and

TRE 20 (Figure 16 c) types are the width of concrete in the full height in the whole length of the beam, where TRE 10 has 10 cm, and TRE 20 has 20 cm.



(d) (e)

Figure 16 - Composite beam cross-sections: Solid slab (MAC) (a); Ribbed slab 10 cm (TRE 10) (b); Ribbed slab 20 cm (TRE 20) (c); TRE Slab framework (d); MAC slab framework (e).

The solid slab is a reinforced concrete slab, where the rate and arrangement of the reinforcements were based on the Push-out Test from Eurocode 4 (2004) since these tests are preliminary tasks for flexural tests that are the object of this study. And for TRE slabs, it was used the same height but using ribbed slabs similar to a precast ribbed slab made by lattice joist, very common in the construction of small buildings in Brazil.

For solid slabs, the bars at positions N1 and N3 had a diameter of 6.3 mm, while N2 had a diameter of 8.0. N1 and N3, the stirrups were spaced at 20 cm, and the N2 was placed in the longitudinal length of the beam (Figure 16 a).

The second type of slab is a ribbed slab similar to a precast ribbed slab. The reinforcement arrangement used in the ribbed slabs consist of TG8SL – GERDAU® trusses spaced 42 cm from each other 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. Besides, an electro-welded mesh produced with CA-60 steel bars of 3.4 mm diameter and equally spaced in both directions each 20 cm was used. This mesh is commonly used to prevent excessive cracking due to the concrete shrinking.

Two identical steel plates are welded on their smooth faces to obtain the same roughness on the two faces of the connector, producing a connector with a ribbed surface on both sides.

That ensures the symmetry of the model and the similarity of features in the connector-concrete surface for shear resistance.

Whereas each checkered steel plate that composes the linear connector is 3 mm thick, so the total thickness will be 6 mm. It covers the whole longitudinal length of the beam with a height of 50 mm. It should be noted that the surface of the plate has ribs with a height of 1 mm in 45º equally spaced and intercalated as a function of the direction, as seen in Figure 15. This roughness present in the connector serves to provide the transfer of shear between the involved interfaces.

Concerning to the steel-based profile, the one used in the present research corresponds to the W150x13 (ASTM-A572 grade 50). The profile used in each model has a total length of 290 cm, where the connector welded to the steel-based profile can be seen in Figure 17.

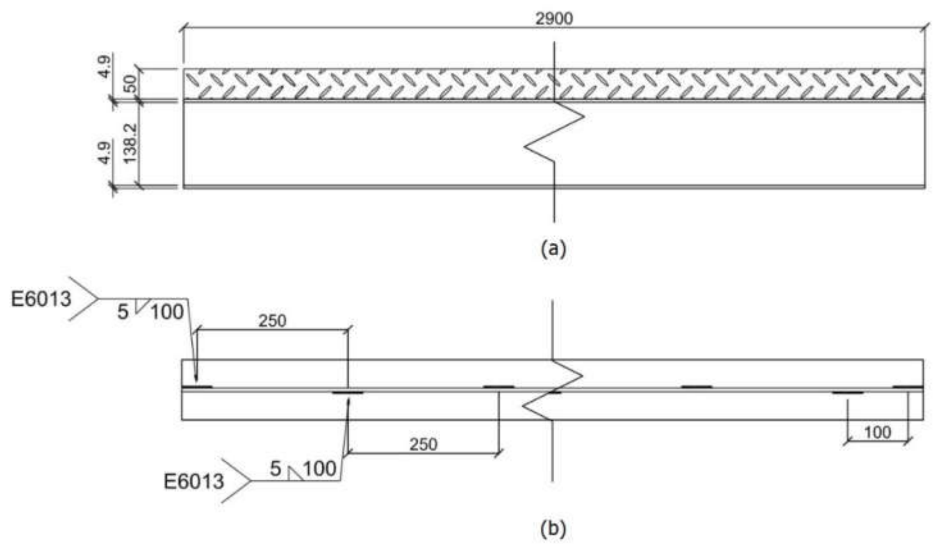


Figure 17 - Connection between steel profile and steel plate connector; (a) lateral view. (b) Top view. Dimensions in mm

3.3 MATERIAL PROPERTIES

For the concrete, Standard cylinder specimens were cast simultaneously with the composite beams. Concrete was ordered from a Brazilian firm with the nominal grade of C30. The concrete specimens were used to evaluate density, modulus of elasticity, and compressive strength. About the compressive strength, when the tests were performed, the values indicated that the class of the concrete was C25/20.

The average compressive strength and elasticity modulus from six specimens were obtained from cylindrical samples, using the recommendations of ABNT - NBR 5739:2007 (Concrete Cylindrical specimen compression test), ASTM - C215-08 (Standard test method for fundamental transverse , longitudinal, and torsional resonant frequencies of concrete specimens) and compressive strength directly from de slabs according to ABNT - NBR 7584:2012 (Hardened Concrete - Evaluation of surface hardness by reflection sclerometer).

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 (Sonelastic, 2014) (Figure 17). Finally, the tensile strength of the steel profile and connectors was referenced to ASTM A36 and A572 grade 50, respectively. Table 10 summarizes the mechanical properties of all the materials used in the connection.

Figure 18 - Sonelastic® test setup

Table 10. Material Properties

Specimen	**$E_{long,din}$ (GPa)**	***f_{cm}* by cylindrical samples(MPa)**	***f_c* of slabs by sclerometry (MPa)**	***Density (kg/m³))***
Concrete	27.92 ± 2.66% *	24.08 ± 21.37%*	24.14 ± 3.28%*	2263.33 ± 1.1%*
Steel	**Nominal value of Ultimate Tensile Strength (MPa)**			
Beam	450			
Connector	400-550			

*Average and Coefficient of Variation (CV), respectively.

3.4 INSTRUMENTATION AND TEST PROCEDURES

The tests in this study consisted of a static and dynamic evaluation of composite beams. The methodology of this work is described briefly in the flowchart (Figure 19).

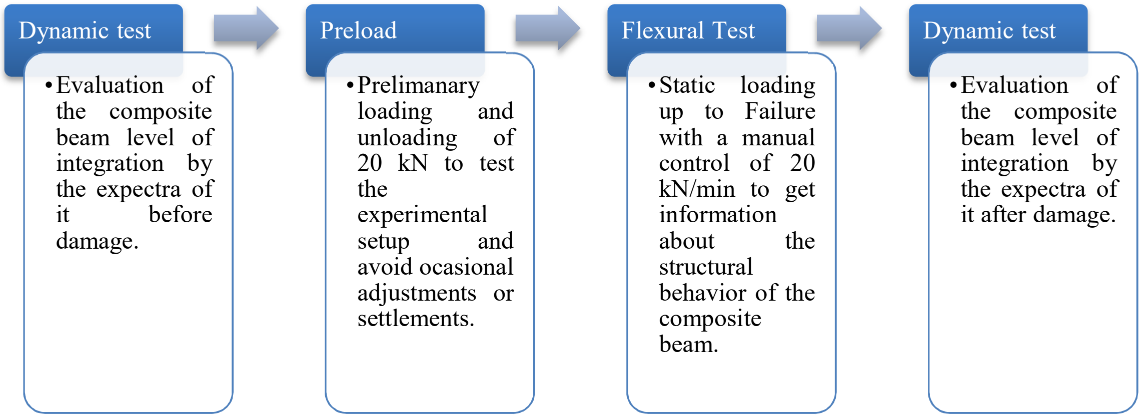


Figure 19 - Methodology flow chart

More detailed information about the static test and dynamic tests are described in the topics 3.4.1 and 3.4.2, respectively.

3.4.1 Flexural Tests

The flexural tests were performed with a simply supported beam and a four-point loading configuration. Monotonic load steps were set in the third spans and applied with manual load control (Figure 20 and Figure 21). For all samples, it was used web stiffeners (Figure 21) in support regions to prevent the web crippling phenomena.

Seven measurer devices were used to measure slip, uplift, and vertical displacement of the tested composite beams (Figure 22). Slip and uplift measurements were taken on both sides of the specimens at the support region, and the uplift was also measured at 10 cm from mid-span, the distance of 10 cm was to allocate de measurer device of the vertical displacement of mid-span. Vertical displacement was measured at the mid-span and one third-span.

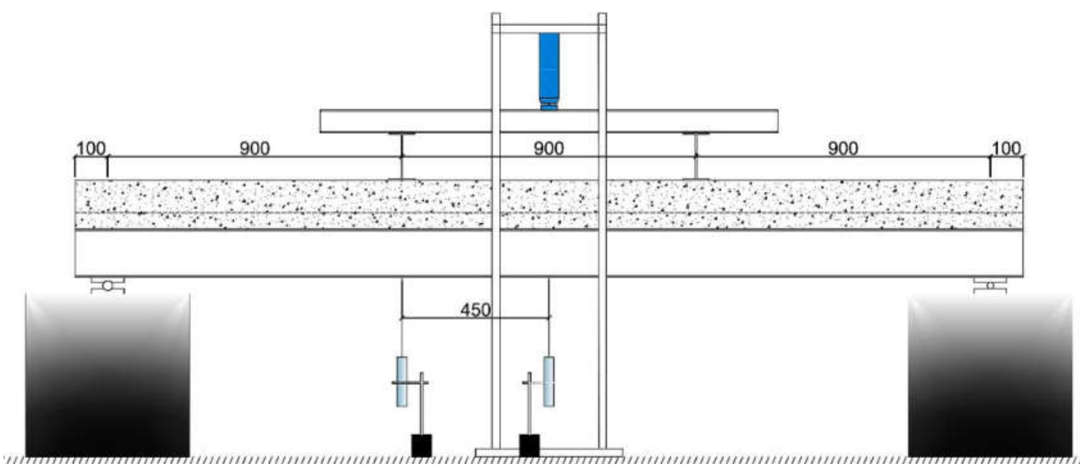
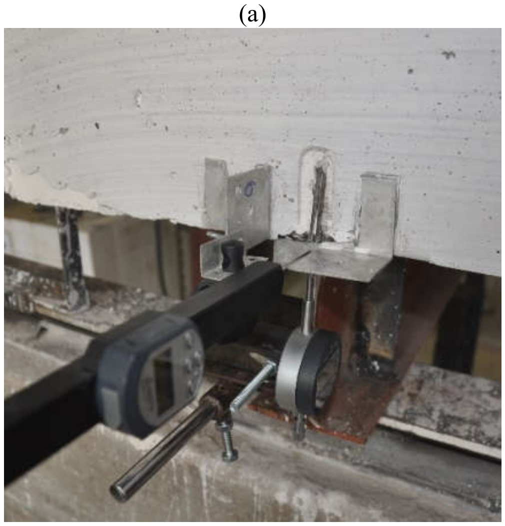


Figure 20 - View of flexural test. Dimensions in mm

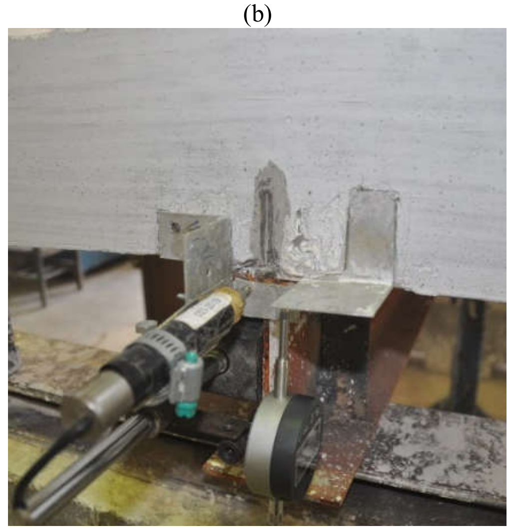
Figure 21 – Overview of Flexural test setup with detail of the web stiffener.

(a)

(b)



(c)



(d)

Figure 22 - Measurer device positions. Uplift at mid-span (a); Third-span and mid-span vertical displacement (b); Slip and uplift at supports (c) (d).

3.4.2 Dynamic Tests

For the non-destructive evaluation, before and after the bending test to verify the level of integration of the composite beam and the residual stiffness of the composite section after the pseudo-static tests. A forced vibration was introduced using a rubber hammer impact in combination with a piezoelectric accelerometer (Figure 23). The acquisition/excitation points of the prototype were the quarter-span, mid-span, and supports.

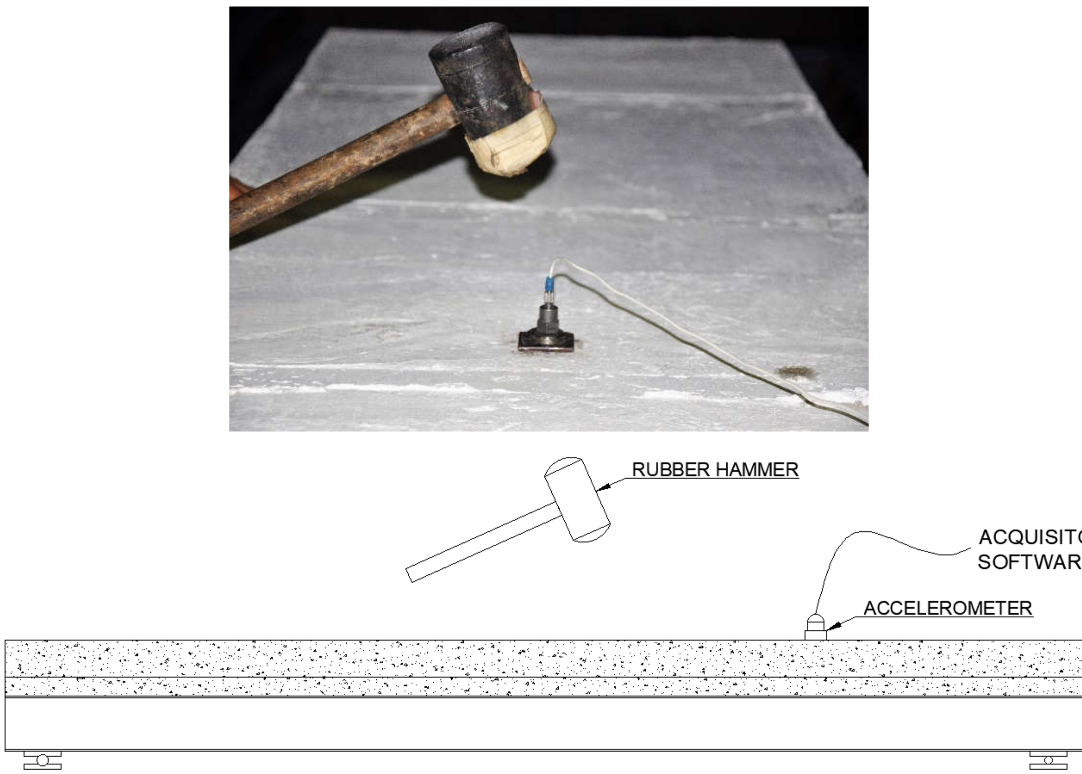


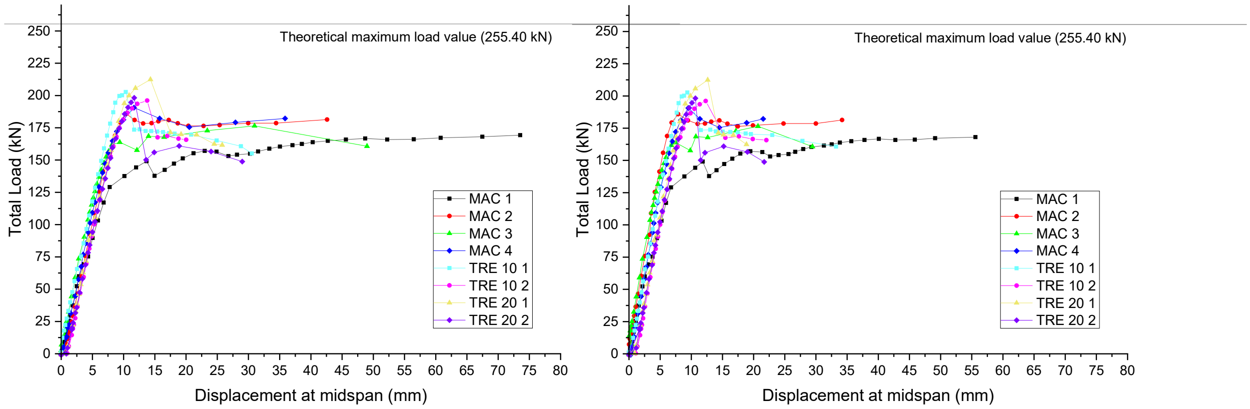
Figure 23 - Piezoelectric accelerometer and a rubber hammer.

3.5 RESULTS AND DISCUSSION

3.5.1 Flexural test

3.5.1.1 Failure modes

Figure 24 plots the values of vertical load and corresponding vertical deflection measured at the mid-span and at one third-span of all tested specimens, and Figure 26 plots the values of vertical load and corresponding slip measured at the beam supports.



(a) (b)

Figure 24 - Load plotted versus mid-span displacement (a); versus third-span displacement (b). Theoretical maximum load value calculated considering a monolithic behavior.

Comparing Figure 24 (a) and (b), it is possible to see that the displacements were smaller in the thirds of the span, but sometimes they were very close to those in the mid-span, what was because in general, all specimens exhibited some asymmetry in slip behavior. Knowing that the value of slip measured at one side of the specimen was higher than the corresponding value measured at the other side and stayed almost with zero slip, as shown in Figure 25 for MAC 2 and for all specimens in Figure 26. That indicates that the connection ceased in not in the mid-span but somewhere between it and the third-span.

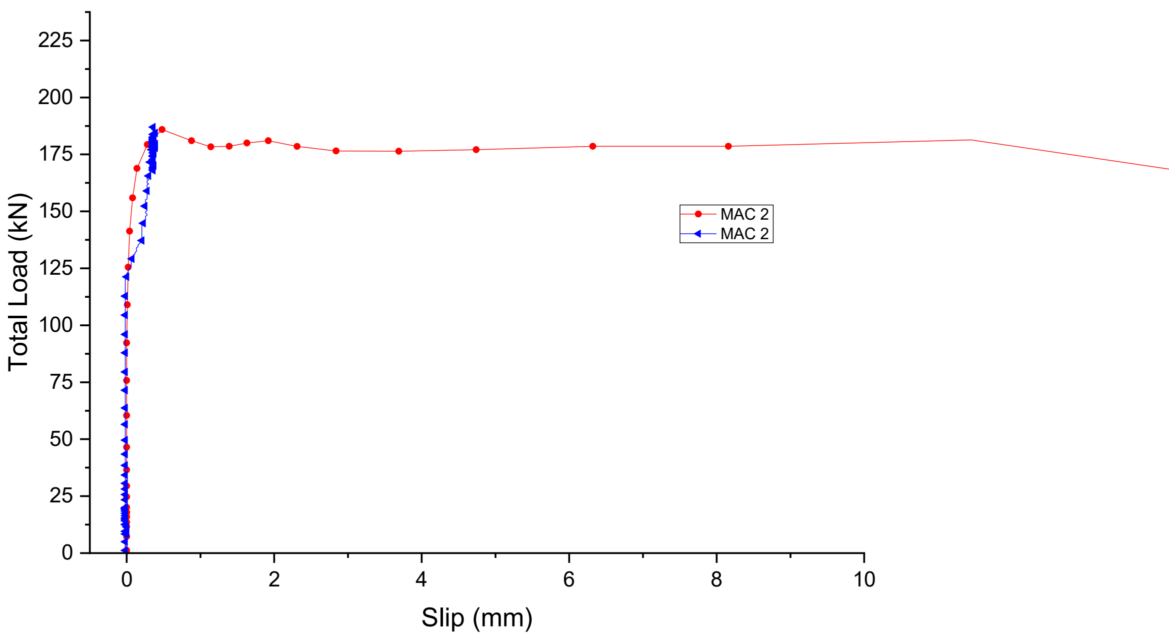


Figure 25 - Slip versus Load for MAC2

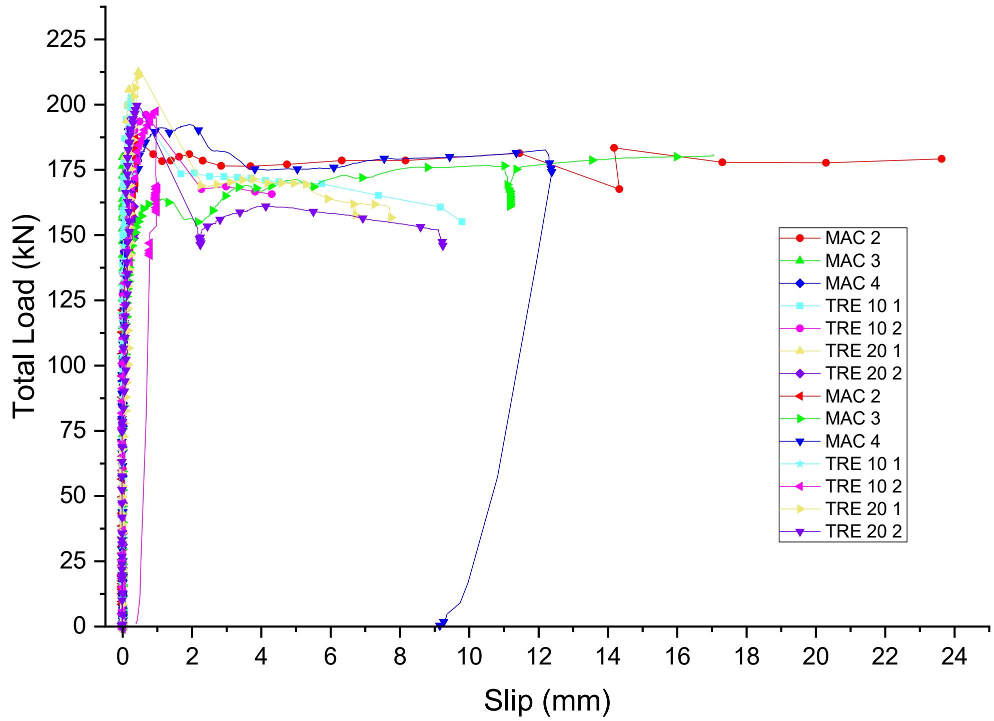


Figure 26 - Load plotted versus slip

Slip of specimen MAC 01 was not recorded because, for this specimen the slip was measured between the concrete slab and the connector, but for all samples with solids slab that was no slip between the connector and slab, so the slip was measured between the slab and the steel beam.

Figure 24-a shows that the specimens initially had almost the same behavior in concern of bending rigidity. Later the damage to the connection occurred first in MAC Beams. Initial cracks in the MAC beams were possible to be observed at 100 kN of Load, but consistent cracking was only able to be seeing around 150 kN for those slabs, until the end of the test the cracking for solid slabs was spread out between the two force application points (Figure 27). For MAC 1 and MAC 3, the connection rupture provoked a significant loss in the load capacity, but not big, in comparison with the other beam with solid and ribbed slabs.

Figure 27 - solid slab cracking

In MAC beams were possible to observe the crushing of the concrete in the upper part of the slab in mid-span (Figure 28).

Figure 28 - Crushing of concrete slab in MAC slabs.

In the case of TRE beams, the damage in the connection was later than in MAC slabs. In comparison with the MAC slab, there was a more significant loss in load capacity when the connection was ruptured. And for those, the maximum load was precisely before the rupture, which did not happen in MAC 1 and MAC 3. The cracks for the TRE beams were concentrated in time because the occurred practically in the moment of connection rupture, and in the thirds of the span, where the load was applied, and starting at one side (Figure 29).

Figure 29 –Ribbed slab Cracking.

Between the two types of Ribbed Slabs, TRE 10 and TRE 20, it was not observed a significant difference between them, which shows that it was possible to maintain the same interaction between the interfaces, even with a smaller amount of concrete.

There were differences in how the connection was broken between the concrete and the steel beam. In TRE slabs, the connection had its rupture in the interface between the steel connector and the concrete (Figure 30 a). But for the MAC slabs, due to the higher amount of concrete, that was differences in the behavior of the connection that provoked stresses that ruptured the connection in the welding of the connector to the steel beam, while it continued attached to the concrete slab (Figure 30 b).

(a) (b)

Figure 30 - Post-peak configuration of connection region for specimen with ribbed slab (a) and solid slab (b).

Because of that behavior, TRE slabs performed better even with a smaller amount of concrete. For being possible to MAC slabs, achieve higher resistances, it is necessary a stronger welding than those used for TRE slabs.

In a general way, all the specimens reached suffered a high degree of damage to the composite section, as seen in Figure 31 (b), there was such displacement that it provoked detachment of protective paint on the bottom flange. And after the tests, the specimens were demolished to observe the condition of the connector and connection (Figure 31 a), since there was still a great connection, some parts of concrete were pulled off. And for the connector, there was not a great damaged in it, but it followed the deformation of the beam.

(a) (b)

Figure 31 – Configuration of beam and connector after the flexural test. (a) demolished composite beam; (b) detachment of protective paint on the bottom flange.

3.5.1.2 Maximum flexural strength and degree of interaction

From the analytical approach, according to annex of Brazilian code NBR 8800 (ABNT, 2008) (APPENDIX A), the composite beams should achieve 114.93 kN.m of bending moment strength that corresponds to a total load applied of 255.40 kN. These calculations considered full interaction in the shear connection and stress distribution in the cross-section according to Figure 32. In this study the Plastic Neutral Line (PNL) was situated in the concrete slab. Besides, the average values of the properties of the material were considered. These values were collected from experimental tests performed on the concrete and steel specimens cut from the steel profile and the steel connector used in the experimental campaign.

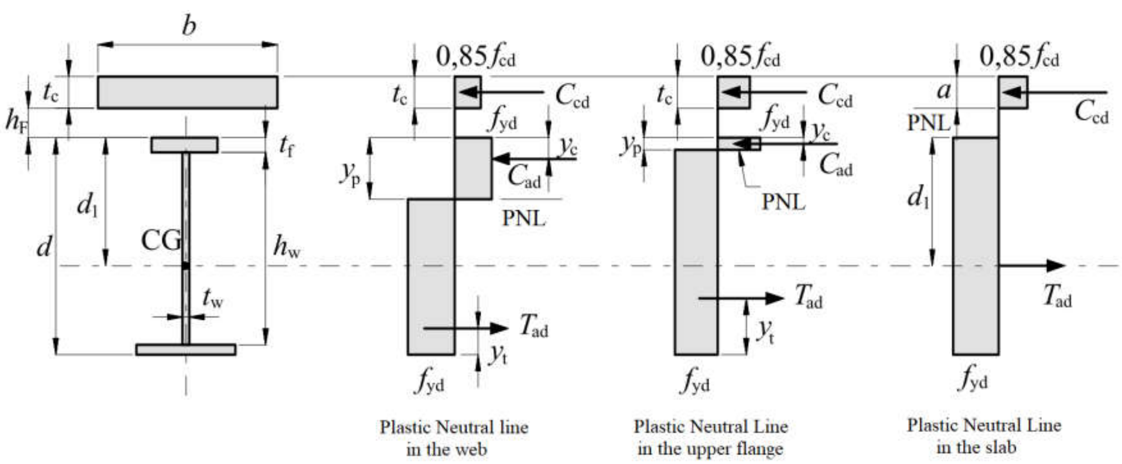


Figure 32 - Stress distribution in the cross-section under sagging moment according to annex O of NBR 8800 (ABNT, 2008).

For comparison, the maximum load value of 212.8 kN obtained by TRE 20 1 provoked a bending moment of 95.4 kN.m, which is close to the value obtained for the nominal plastic bending moment of the composite beam considering full interaction. Besides, if it were considered the steel beam alone, the plastic bending moment would be just 33.25 kN.m, approximately one-third of the maximum bending moment obtained in the experimental program.

The values of flexural stiffness and maximum load obtained in the bending tests performed on composite beam specimens are presented in Table 11. All the results refer to the results for the mid-span of the beam.

The specimens with ribbed slabs attained the highest load capacity. For the two types those slabs, there was a significant difference in this aspect. For all MAC slabs, it was observed that a rupture in the welding, which caused a smaller load capacity, showing that for a higher amount of concrete, it is necessary a stronger welding.

Also, in Table 11 is shown the level of interaction calculated as the maximum bending moment divided by the theoretical plastic bending moment (95.4 kN.m). For the composite beam with ribbed slabs, it was possible to obtain a better result in terms of interaction. What is excellent evidence that the use of connections by adherence in the context of ribbed slabs is promising.

Table 11 - Maximum flexural strength and level of interaction

Specimen	Maximum applied Load (kN)	Average Maximum load (kN)	Maximum bending moment at mid-span (kN.m)	Average maximum bending moment at mid-span (kN.m)	Mid-span vertical Displacement for Connection rupture (mm)	Mid-span vertical Displacement for Maximum Load (mm)	Level of interaction (%)
MAC 01	177,0	184,6	79,65	83,06	13,67	73,53	69,30
MAC 02	187,2		84,24		10,43	10,43	73,30
MAC 03	181,8		81,81		9,39	20,70	71,18
MAC 04	192,3		86,54		11,67	11,67	75,29
TRE 10 1	203,0	200,2	91,35	90,09	10,35	10,35	79,48
TRE 10 2	197,4		88,83		13,78	13,78	77,29
TRE 20 1	212,8	206,3	95,76	92,81	14,30	14,30	83,32
TRE 20 2	199,7		89,87		11,70	11,70	78,19

Even though the solid slabs did not reach a level of integration as the ribbed slabs, because it would need stronger welding, one must point out that the shear connection obtained with those slabs was higher too. In comparison with the beam alone, the maximum load supported was more than doubled. So with the gain in speed and decrease in the cost of construction turns the use of spaced welding as used in this work also a good option for composite beams with solid slabs.

In other works as from Diógenes *et al.* (2018) and Thomann and Lebet (2008) with connection by adherence, it was possible to reach a level of interaction close to 100 %, i. e., full shear connection. It did not reach that level of connection in this work, that could be to the fact that in those studies the there was also resistance in the interface between the top flange of the beam and the concrete, as shown in Figure 9. it was put a tape between the two elements.

In this work, to ensure that the connection of the composite beam would be just from the interface of the concrete-connector, it was put a tape between the upper part of the beam and the concrete slab. In that case, there was significant interaction between the slab and the upper part of the steel beam.

3.5.1.3 Uplift and slip

Figure 33 compares the evolution of slip and vertical displacement in the beam mid-span, indicating a linear relationship between the uplift and vertical displacement and that the slip was only observed generally after 10 mm of vertical displacement. In Figure 33, it is only compared to the slip of one side of the beam, since the acquisition from the other side was different.

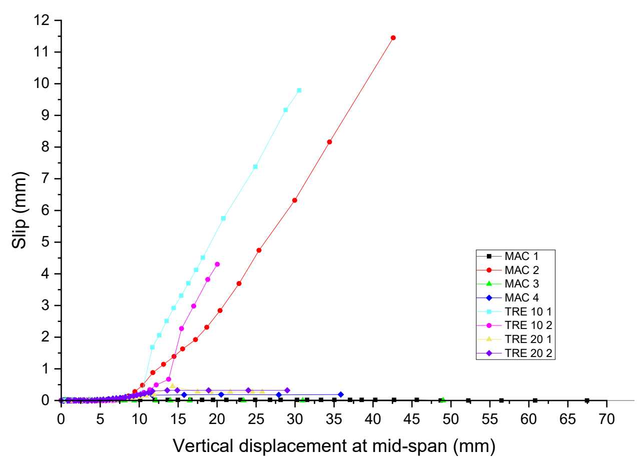


Figure 33 - Slip versus vertical displacement at mid-span

It was not possible to find a good relation to uplift values. For the uplift measured at support (Figure 34), it was observed that the rotation of the steel beam was higher than the slab's, so that provoked a misreading for the uplift. However, there was no visual uplift at the supports before the connection rupture.

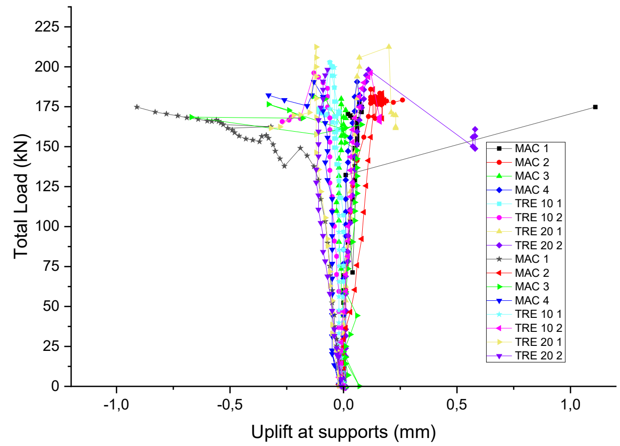


Figure 34 - Uplift measured at supports versus total load applied

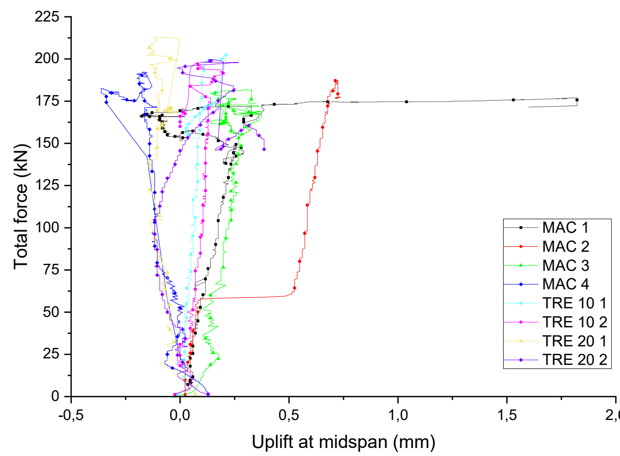
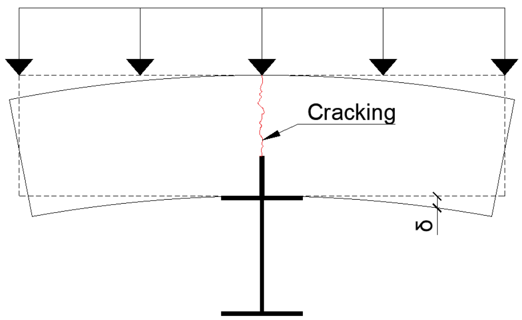
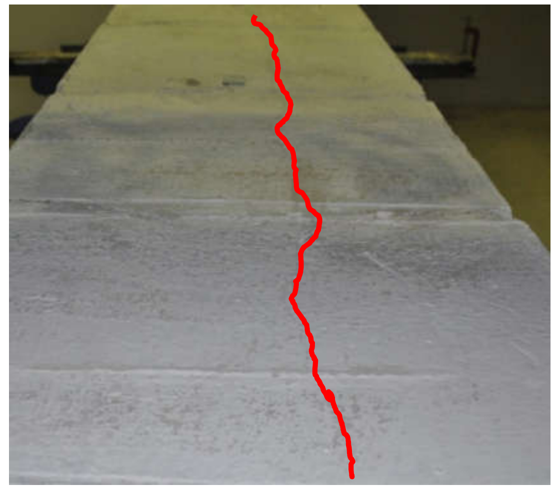


Figure 35 - Uplift at mid-span versus total load applied

Regarding the measure in the mid-span (Figure 35), there was not the influence of rotation, but again some of the results were negative, which represents approximation between the steel beam and the concrete slab. However, since the slab is right on top of the steel beam, it shows that was bending in the transversal axis of the beam, one evidence of that is the crack in the longitudinal axis of some beams (Figure 36), that behavior was observed in TRE and MAC slabs.



(a)



(b)

Figure 36 - Crack in the longitudinal axis of the composite beam

3.5.2 Dynamic Test

Figure 37 displays the spectra of the accelerometer for quarter-span, mid-span, and supports for each prototype with solid slabs (MAC's) before and after the flexural test, i.e., undamaged and damaged, respectively. And in Figure 38 is in the same way for prototypes with ribbed slabs (TRE's).

The damaged spectra of MAC 1 was not acquired in that prototype, because in that one, it was aimed to see what would happen if the beam were forced a lot after the plastification of the section, so the test continued until the connector was pulled off for more than half of the beam. In that way, the concrete slab was detached from the steel beam. So there was not any more integration from the composite connection, and the test of the damaged MAC 1 was not performed.

It is possible to see that the spectra from the undamaged prototypes to damaged ones were dislocated, which is due to the loss in the bending rigidity after the specimens, confirming that there was damage in the connection.

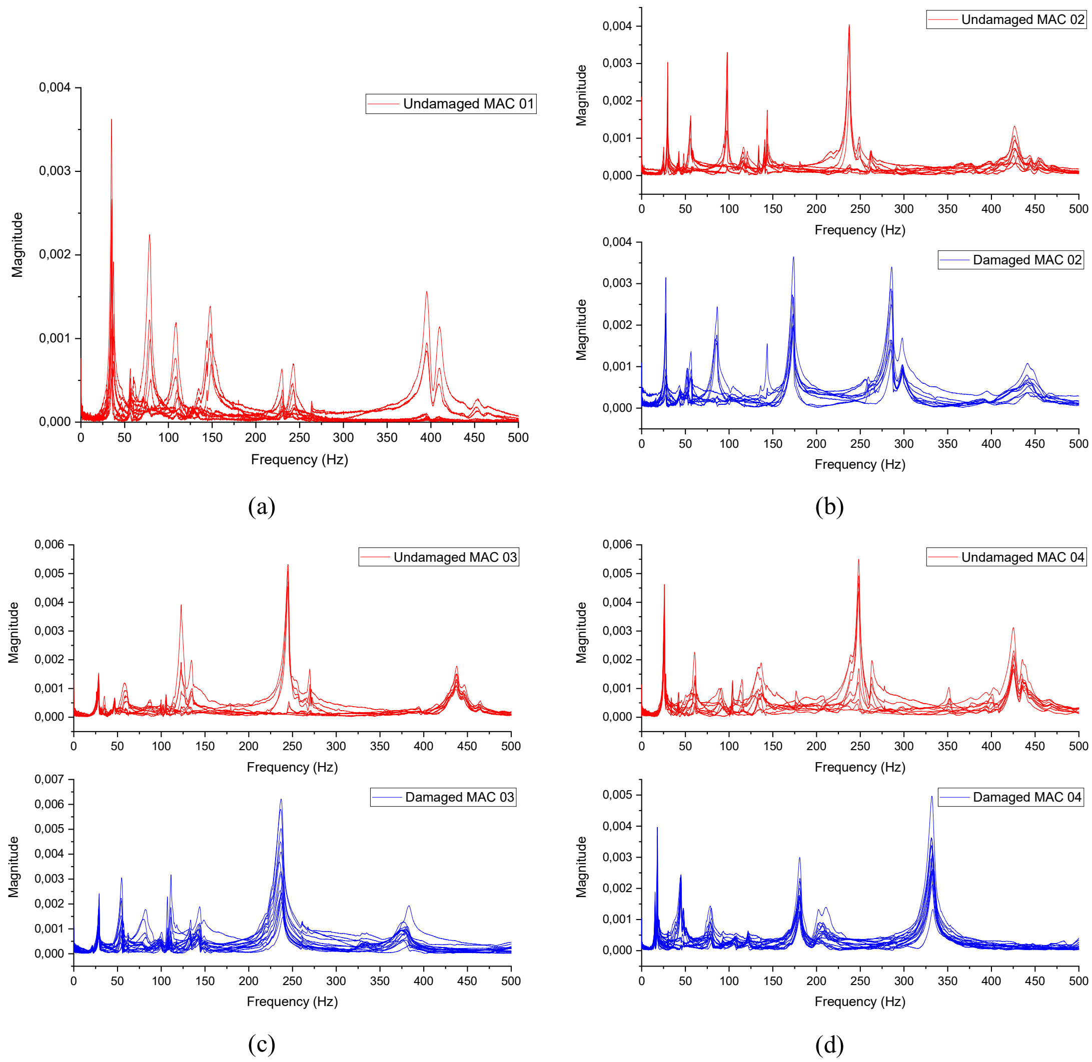
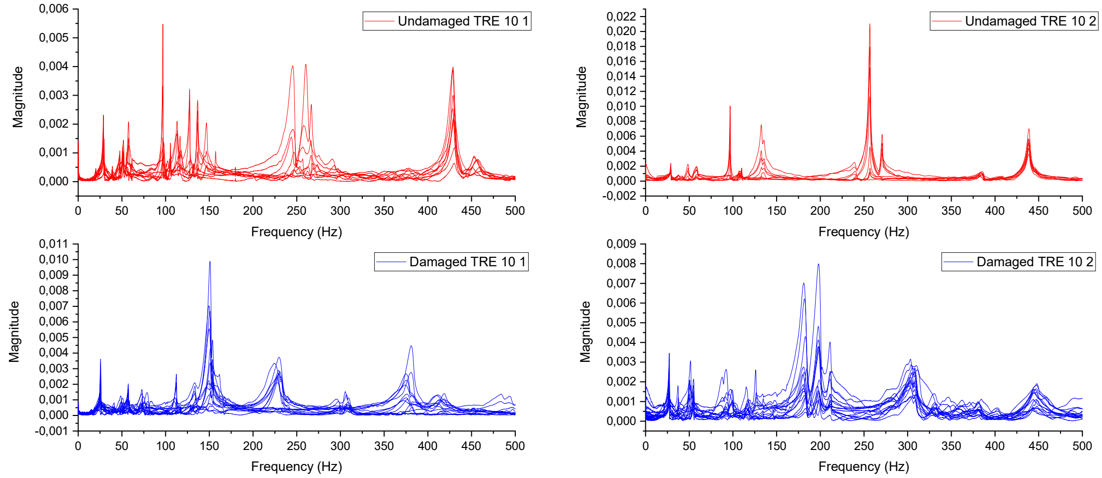
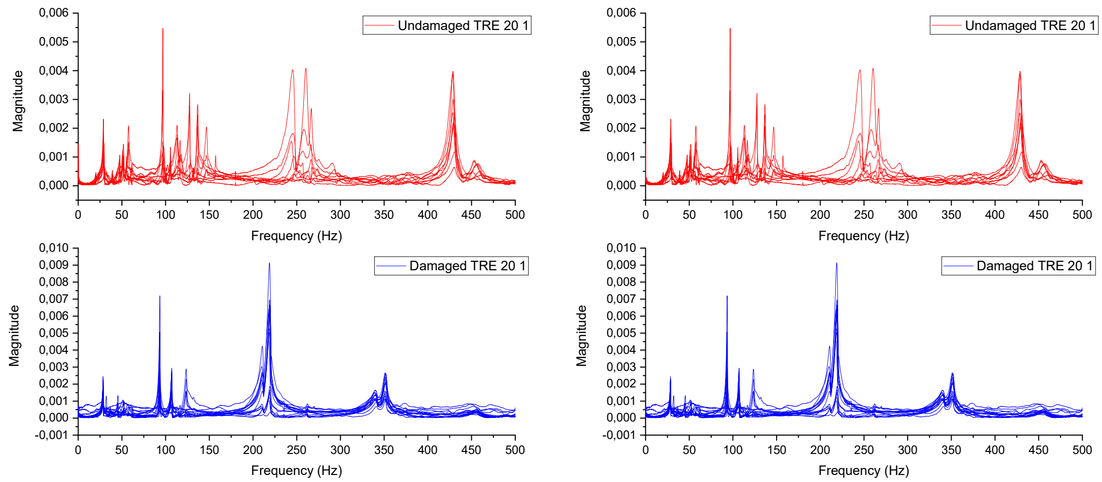


Figure 37 – Damaged and undamaged spectra of prototypes; (a) MAC 1; (b) MAC 2; (c) MAC 3; (d) MAC 4.



(a) (b)



(c) (d)

Figure 38 – Undamaged and damaged spectra of prototypes; (a) TRE 10 1; (b) TRE 10 2; (c) TRE 20 1; (d) TRE 20 2.

Determining the natural flexural frequencies associated in the context of this research is relatively challenging, considering that it is a composite section that features several located modes of vibration with frequencies very close to each other. However, an analytical calculation was performed to obtain obtained natural frequencies and vibration modes associated with them.

Table 12 shows the values obtained from the Analytical simulation (APPENDIX B). It was considered perfect adherence between the elements that compose the beam-slab connection for this calculation.

Table 12 – Frequencies obtained by analytical calculation.

	Frequency (Hz) MAC	TRE 10	TRE 20
1st mode	49.62	56.84	55.11
2nd mode	198.48	227.39	220.45
3rd mode	446.59	511.64	496.01
4th mode	793.94	909.58	881.81

It is noted worthy that for a smaller amount of concrete, the values of frequency were higher, so the ones with the best performance were TRE 10. that is because the loss of inertia is not equivalent to the loss of mass in the structure that increases the frequency.

But in the utilization of structures, the weight of it is not only the self-weight, it is added other dead and live loads. So the decrease in the weight of only that structure would not be so representative in the behavior of its frequency.

However, it was observed too many peaks between 0 and 200 Hz, as seen in Figure 37 and Figure 38. In this way, the analysis of the vibrational behavior of the composite beam prototypes will be given by evaluating the natural frequency associated with the third flexural mode, the most representative in the spectra, that, according to the calculation should be between 450 Hz and 515 Hz.

Table 13 shows the frequencies obtained by analyzing the peaks in the spectra from the dynamic tests of undamaged and damages prototypes. It also showed the average reduction in the frequency for each type of slab.

Table 13- Natural frequencies associated with the third mode of vibration

Prototype	MAC 1	MAC 2	MAC 3	MAC 4	TRE 10 1	TRE 10 2	TRE 20 1	TRE 20 2
Undamaged (Hz)	409.75	426.62	437.75	425.12	428.87	438.75	428.87	434.50
Damaged (Hz)		286.37	383.25	331.87	381.00	303.75	351.00	359.00
Reduction in natural frequency.		32.87%	12.45%	21.93%	11.16%	30.77%	18.16%	17.38%
Average reduction in natural frequency	22.42 % ± 10.22 %*				20.97 % ± 13.86 %*		17.77 % ± 0.55 %*	

*Average and Coefficient of Variation (CV), respectively.

Regarding the fact that the natural frequencies from the tests be a little bit smaller than the one in the analytical calculation, could the fact that in the calculus was considered full interaction, and as shown in the flexural test, the maximum value of the level of interaction was 83,32%. Thus, it was expected that the frequencies would be smaller.

The reduction of frequency value in terms of stiffness (EI) - the product of modulus of elasticity by inertia - corresponds to a loss of bending rigidity of 47,34 %, 45,78%, and 42.15% for the prototypes with MAC, TRE 10 and TRE 20 slabs, respectively. It is emphasized that the stiffness, in this case, is proportional to the square of the natural frequency, if one considers the formulation of Euler-Bernoulli for simply supported beams. The presence of residual stiffness detected in non-destructive testing indicates that there is still interaction between surfaces of the composite section at the end of the static test.

3.6 CONCLUSIONS

The proposed connection by adherence obtained by a checkered connector allowed all the tested beam specimens to achieve a composite section with a high degree of interaction and strength.

The specimens with ribbed slabs (TRE 10 and TRE 20) showed the highest load capacity. From the two types of composites beams, there wasn`t a significant difference, so it was able to reach a high degree of interaction even with a smaller amount of concrete.

For the specimens with solid slabs (MAC), the result of shear connection was smaller, but that was due to the resistance of the welding, which in this case should be better than in TRE types, and with this higher values than reached in TRE types should be obtained.

It is also essential to be aware of the fragile behavior of the connections by adherence in this study, characterized by small values of slip until some damaged in the connection and the abrupt rupture in the connection, more visible in TRE beams,

For the non-destructive dynamic tests were able to capture and quantify, in a simplified way, the influence of flexural test on the composite beam stiffness by the shrinkage of the spectra toward peaks with smaller frequencies. With this, building structures that are still in service after some damage could be verified by a dynamic analysis to get the residual stiffness of the structure.

Regarding the degree of interaction, it is believed that they can also be determined, in a simplified way, for damaged and undamaged specimens that can give us some information about the residual stiffness in the composite beam. However, it is necessary a more comprehensive dynamic experimental analysis with the determination of the vibration modes of the isolated elements, beam and slab, besides the composite section, that can lead us to more precise results.

At last, it is believed that connection by adherence obtained by a checkered plate is a viable option for structural engineering in the context of solid and ribbed slabs. However, more research should be carried out, especially the connection fatigue behavior and the response under long-term loading.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

During the development of the present investigation and following the objectives established in item 1.2, it was sought to characterize the flexural behavior of a new alternative for connections by steel-concrete adherence, through a systematic review of the literature and an experimental program. First, it was conducted a systematic review about how is the flexural behavior of connections by adherence to get evidence on how this type of connection could improve composite connection.

Later with the information of the review, it was evaluated a new type of connection by adherence through an experimental program. The studied composite connection consists of the application of a checkered steel plate as a shear connector between a steel beam and a concrete slab. In the context of the concrete slab, it was evaluated the use of ribbed type.

Regarding the systematic review, the synthesis of some studies and their respective methodologies allowed a new way of thinking about adherence connection and its flexural behavior, since the study about that type of connections is relatively new, this work covered all straight connectors to make a comparison between those connectors. Even though the number small of selected works to review, it was possible to answer how is the flexural behavior of connections by adherence.

From the systematic review, it was possible to perform a qualitative analysis about Load and vertical displacement, slip, and uplift, fatigue behavior, cracking patterns and failure model, level of interaction, and longitudinal shear resistance of the selected works. After that discussion, it was possible to deduce that connections by adherence shows good performance in comparison with other types of linear connector and other common used connector such as stud type.

Regarding the experimental approach, the flexural behavior of the alternative studied had good results regarding the degree of shear connection and considering that in this study, there was not an interaction between other interfaces than connector-concrete slab different from Diógenes *et al.* (2018) and Thomann and Lebet (2008).

The specimens with ribbed slabs performed better regarding the maximum load, even though there was a smaller amount of concrete. Analyzing the two types of TRE slabs, with different quantities of concrete, it was proved that with different thickness of concrete it was possible to have the same interaction, the minimum used in this work was 10 cm, that was able to transmit the shear stresses to a concrete slab of 15 cm high.

Even though the composite beams with solid slabs, MAC's, had inferior results in this work, the rupture was not in the interface connector slab as were in TRE slabs. The stresses were higher in the welding, probably because of the bigger confinement due to the higher quantity of concrete, allowing smaller slip between the connector and the concrete slab. So if there were a stronger welding for this case, probably there would be better results.

Regarding the behavior of the beams, that was also differences in the rupture. For TRE types with higher performances came more fragile behavior, and for MAC beam, the response was different, but probably it would be the same with stronger welding.

The non-destructive dynamic tests were able to capture and quantify, in a simplified way, the influence of damage on the composite beam stiffness, so that it can help the analysis of these structures with non-destructive tests where destructive one are not able to be performed.

Thus, from the experimental program and the systematic review, which evaluated and discussed aspects of the structural flexural behavior of connection by adherence and a new alternative for that type of connection. At last, it can be said that straight connectors formed by ASTM - A36 chess type plate performed can be used in composite formed with solid or ribbed slabs, being a viable option for structural engineering.

4.1 Recommendations for future work

Assuming that no work is complete, it is understood that all research work should provide directives for future work that directly or indirectly involve the research topic studied. Here are some suggestions for future research.

- 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 39.a) for confinement levels ranging from 0,5 to 5 N/mm^2 is the way to be followed 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.

It is suggested to perform pullout tests (Figure 39.b) to Complement the results from direct shear tests, to evaluate the direct tensile strength of the composite connection developed, which is interesting to know due to uplift.

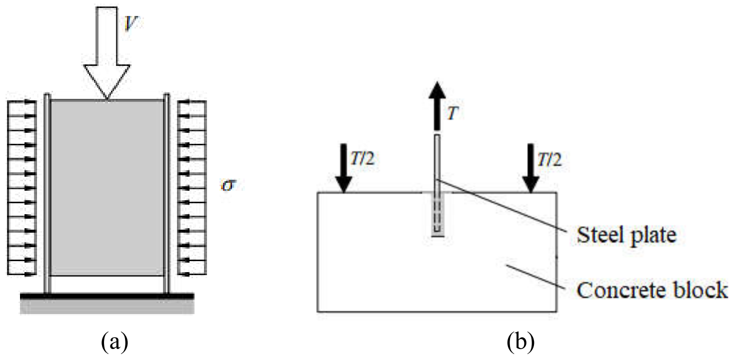


Figure 39. (a) Principle of the direct shear test principle. (b) Principle of the pullout test.

- Flexural test

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. Also, to evaluate the structural behavior of the composite connection considering the presence of holes and transverse reinforcement.

- Finite element analysis

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

- Economic analysis

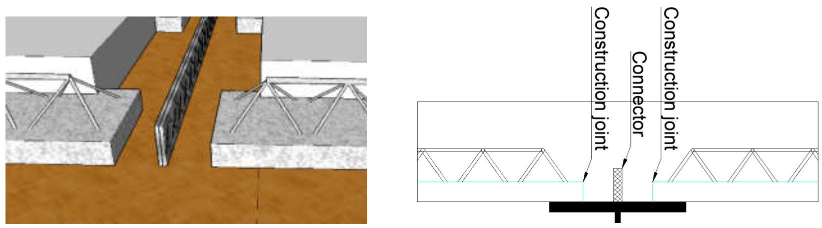
Economic and commercial feasibility study on the use of linear connectors formed by ASTM - A36 chess type plate in building construction.

- Analysis of Fatigue and Fluency;

As can be seen throughout the development of this work, the proposed connection presents a fragile behavior. Therefore, the evaluation of proposed adherence connection in terms of its behavior, fatigue, and long term loads (creep) is imperative. As the advance of structural engineering provides increasingly sophisticated and flexible structures, therefore, more subject to fatigue problems.

- Slab type change

The ribbed slab was studied in this work, but this slab is usually associated with precast part of concrete. One point that should be taken into consideration for this difference is the existence of a construction joint near the connector when using this type of slab, as illustrated in Figure 40. So it should be evaluated the use of this precast ribbed slab associated with connections by adherence.



(a) (b)

Figure 40 - Precast ribs associated with a connector.

Finally, it is believed that the field of study of adherence connection is still quite incipient, i. e., it leaves a wide range of alternatives to be studied in future works.

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APPENDIX A – Composite Beam Bending Strength

COMPOSITE BEAM BENDING STRENGTH UNDER SAGGING MOMENT ACOORDING TO ANNEX O FROM ABNT NBR 8800:2008

Initial data:

$t_w := 4.3\ mm$	web thickness
$b_e := 0.6\ m$	Effective Slab Width
$t_c := 0.15\ m$	Slab height
$h := 0.148\ m$	Steel beam height
$\phi := 1$	Steel safety factor
$A_g := 16.6\ cm^2$	Steel cross-sectional area
$f_y := 345\ MPa$	Steel yield strength
$\phi_c := 1$	Concrete Safety factor
$f_{cm} := 24.08\ MPa$	Average concrete compressive strength
$E := 210\ GPa$	

$\frac{h}{t_w} = 34.419$; $3.76 \cdot \sqrt{\frac{E}{f_y}} = 92.766$

Simply supportes beam with shored construction.

With $\frac{h}{t_w} < 3.76\sqrt{\frac{E}{f_y}}$, the W 150x13 is considered a compact section, so the Composite Beam Bending Strength is calculated according to this following steps. The coefficient of 0.85 of f_{ck}, primarily corresponds to the long-term effects (Rüsch effect).

With the Plastic Neutral Line in the concrete slab, that is the case in this study the distribution of stress is according to figura O.4, isto é:

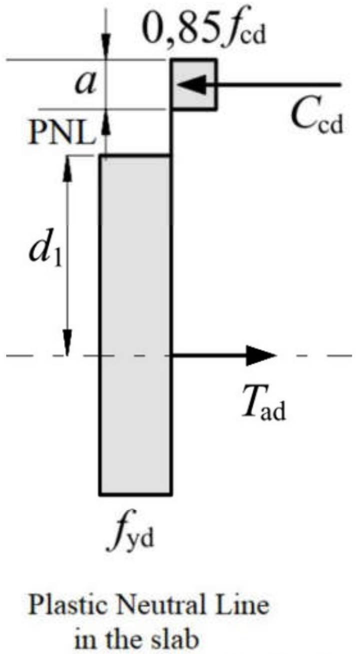

Figure A-1 - Stress distribution in the cross-section under sagging moment according to annex O of NBR 8800 with PNL in concrete slab (ABNT, 2008).

$$C_{cd} = 0.85 \cdot f_{cm} \cdot b_e \cdot t_c = \left(1.842 \cdot 10^3\right)\ kN$$

$$T_{ad} = A_g \cdot f_y = 572.7\ kN$$

With $C_{cd} > T_{ad}$, the following steps can be used for calculation:

$$a := \frac{\phi \cdot A_g \cdot f_y}{\phi_c \cdot 0.85 \cdot f_{cm} \cdot b_e} = 0.047\ m$$

$$e_2 := h + t_c - \left(\frac{a}{2}\right) = 0.275\ m$$

$$e_1 := \frac{h}{2} = 0.074\ m$$

$M_r := \phi \cdot A_g \cdot f_y \cdot \left(e_2 - e_1\right) = 114.931\ kN \cdot m$ Bending resistance of composite section

$P := \frac{M_r \cdot 2}{0.9\ m} = 255.403\ kN$ Applied force in four-point flexural test

APPENDIX B – Natural Frequency Calculation

NATURAL FREQUENCY CALCULATION

$E_{cs} := 28\ GPa$ Concrete Dynamic Modulus of Elasticity

$E_s := 210\ GPa$ Steel Modulus of Elasticity

$I_{aço} := 635\ cm^4$ Steel Beam Moment of Inertia

$$\alpha_e := \frac{E_s}{E_{cs}} = 7.5$$

MAC SLABS

$$x_1 := \frac{\frac{b_e \cdot t_c^2}{2} + \alpha_e \cdot A_g \cdot \left(t_c + \frac{h}{2}\right)}{b_e \cdot t_c + \alpha_e \cdot A_g} = 0.093\ m$$

$$I_x := \frac{b_e \cdot t_c^3}{12} + b_e \cdot t_c \cdot \left(x_1 - \frac{t_c}{2}\right)^2 + \alpha_e \left(I_{aço} + A_g \cdot \left(t_c + \frac{h}{2} - x_1\right)^2\right) = \left(4.592 \cdot 10^4\right)\ cm^4$$

- Section:

$A_c := b_e \cdot t_c = 900\ cm^2$ Concrete Cross-sectional Area

$L := 2.7\ m$ Span Length

$\gamma_c := 25\ \frac{kN}{m^3}$ Concrete Specific weight

$m := \gamma_c \cdot A_c + 13\ kg \cdot \frac{\mathbf{g}}{m} = \left(2.377 \cdot 10^3\right)\ \frac{N}{m}$ Beam weight per meter

- Natural Frequency:

$$f_1 := \frac{(1 \cdot \pi)^2}{2 \cdot \pi \cdot L^2} \cdot \sqrt{\frac{(E_{cs} \cdot I_x) \cdot \mathbf{g}}{m}} = 49.621\ Hz$$

$$f_2 := \frac{(2 \cdot \pi)^2}{2 \cdot \pi \cdot L^2} \cdot \sqrt{\frac{(E_{cs} \cdot I_x) \cdot \mathbf{g}}{m}} = 198.485\ Hz$$

$$f_3 := \frac{(3 \cdot \pi)^2}{2 \cdot \pi \cdot L^2} \cdot \sqrt{\frac{(E_{cs} \cdot I_x) \cdot \mathbf{g}}{m}} = 446.592\ Hz$$

$$f_4 := \frac{(4 \cdot \pi)^2}{2 \cdot \pi \cdot L^2} \cdot \sqrt{\frac{(E_{cs} \cdot I_x) \cdot \mathbf{g}}{m}} = 793.941\ Hz$$

TRE 10 SLABS

$$x_1 := \frac{b_e \cdot \frac{(7\ cm)^2}{2} + 10\ cm \cdot 8\ cm \cdot 11\ cm + \alpha_e \cdot A_g \cdot \left(t_c + \frac{h}{2}\right)}{b_e \cdot 7\ cm + 10\ cm \cdot 8\ cm + \alpha_e \cdot A_g} = 0.082\ m$$

$$I_x := \frac{b_e \cdot (7\ cm)^3}{12} + b_e \cdot 7\ cm \cdot \left(x_1 - \frac{7\ cm}{2}\right)^2 + \frac{10\ cm \cdot (8\ cm)^3}{12} + 10\ cm \cdot 8\ cm \cdot (x_1 - 11\ cm)^2 + \alpha_e \left(I_{aço} + A_g \cdot \left(t_c + \frac{h}{2} - x_1\right)^2\right) = \left(4.191 \cdot 10^4\right)\ cm^4$$

- Section:

$L := 2.7\ m$ Span Length

$V := 0.177\ m^3$ Total volume of concrete

$m_c := V \cdot \gamma_c \cdot \frac{1}{2.9\ m} = \left(1.526 \cdot 10^3\right) \frac{N}{m}$ Concrete Slab weight per meter

$m := m_c + 13\ kg \cdot \frac{\boldsymbol{g}}{m} = \left(1.653 \cdot 10^3\right) \frac{N}{m}$ Beam weight per meter

- Natural Frequency:

$$f_1 := \frac{(1 \cdot \pi)^2}{2 \cdot \pi \cdot L^2} \cdot \sqrt{\frac{(E_{cs} \cdot I_x) \cdot \boldsymbol{g}}{m}} = 56.849\ Hz$$

$$f_2 := \frac{(2 \cdot \pi)^2}{2 \cdot \pi \cdot L^2} \cdot \sqrt{\frac{(E_{cs} \cdot I_x) \cdot \boldsymbol{g}}{m}} = 227.396\ Hz$$

$$f_3 := \frac{(3 \cdot \pi)^2}{2 \cdot \pi \cdot L^2} \cdot \sqrt{\frac{(E_{cs} \cdot I_x) \cdot \boldsymbol{g}}{m}} = 511.641\ Hz$$

$$f_4 := \frac{(4 \cdot \pi)^2}{2 \cdot \pi \cdot L^2} \cdot \sqrt{\frac{(E_{cs} \cdot I_x) \cdot \boldsymbol{g}}{m}} = 909.584\ Hz$$

TRE 20 SLABS

$$x_1 := \frac{b_e \cdot \frac{(7\ cm)^2}{2} + 20\ cm \cdot 8\ cm \cdot 11\ cm + \alpha_e \cdot A_g \cdot \left(t_c + \frac{h}{2}\right)}{b_e \cdot 7\ cm + 20\ cm \cdot 8\ cm + \alpha_e \cdot A_g} = 0.085\ m$$

$$I_x := \frac{b_e \cdot (7\ cm)^3}{12} + b_e \cdot 7\ cm \cdot \left(x_1 - \frac{7\ cm}{2}\right)^2 + \frac{20\ cm \cdot (8\ cm)^3}{12} + 20\ cm \cdot 8\ cm \cdot (x_1 - 11\ cm)^2 + \alpha_e \left(I_{aço} + A_g \cdot \left(t_c + \frac{h}{2} - x_1\right)^2\right) = \left(4.288 \cdot 10^4\right)\ cm^4$$

- Section:

$L := 2.7\ m$	Span Length
$V := 0.194\ m^3$	Total volume of concrete
$m_c := V \cdot \gamma_c \cdot \frac{1}{2.9\ m} = \left(1.672 \cdot 10^3\right)\ \frac{N}{m}$	Concrete Slab weight per meter
$m := m_c + 13\ kg \cdot \frac{\boldsymbol{g}}{m} = \left(1.8 \cdot 10^3\right)\ \frac{N}{m}$	Beam weight per meter

- Natural frequency:

$$f_1 := \frac{(1 \cdot \pi)^2}{2 \cdot \pi \cdot L^2} \cdot \sqrt{\frac{(E_{cs} \cdot I_x) \cdot \boldsymbol{g}}{m}} = 55.113\ Hz$$

$$f_2 := \frac{(2 \cdot \pi)^2}{2 \cdot \pi \cdot L^2} \cdot \sqrt{\frac{(E_{cs} \cdot I_x) \cdot \boldsymbol{g}}{m}} = 220.453\ Hz$$

$$f_3 := \frac{(3 \cdot \pi)^2}{2 \cdot \pi \cdot L^2} \cdot \sqrt{\frac{(E_{cs} \cdot I_x) \cdot \boldsymbol{g}}{m}} = 496.019\ Hz$$

$$f_4 := \frac{(4 \cdot \pi)^2}{2 \cdot \pi \cdot L^2} \cdot \sqrt{\frac{(E_{cs} \cdot I_x) \cdot \boldsymbol{g}}{m}} = 881.812\ Hz$$